FLEXIBLE PAVEMENT THICKNESS REQUIREMENTS

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SYNOPSIS

Because of the important influence of subgrade strength on flexible pavement thickness requirements, seven basic principles of subgrade design and construction, that will lead to stronger subgrades, are summarized. The method developed by the Canadian Department of Transport, based on plate bearing tests, for establishing the minimum thickness of flexible pavement needed to carry any specified wheel load over any given subgrade is briefly reviewed. Charts of curves which indicate flexible pavement thickness requirements for both airport and highway loads on single wheels are included for capacity traffic volumes. Methods for modifying these thickness requirements due to the influence of dual, dual tandem, or other multiple wheel assemblies, eccentricity of axle loadings, impact stresses, tandem axles, variations in traffic volume, frost action and climate, braking stresses, thickness of bituminous surfacing, paved shoulders, etc., are described.

Introduction

It is the primary purpose of this paper to outline a method for flexible pavement thickness design. In addition, procedures will be described for taking into account the many variables that influence the flexible pavement thickness requirement for any given set of conditions.

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In this paper, a flexible pavement structure will be understood to consist of three basic elements, the subgrade, the base course, and the wearing surface, as illustrated by Figure 1. To simplify the presentation, the layer of material usually known as the "sub-base," is considered to be included within the base course, of which it is actually the lower portion. In common with usual North American practice, the base course and wearing surface layers *taken together* are referred to as a "flexible pavement."

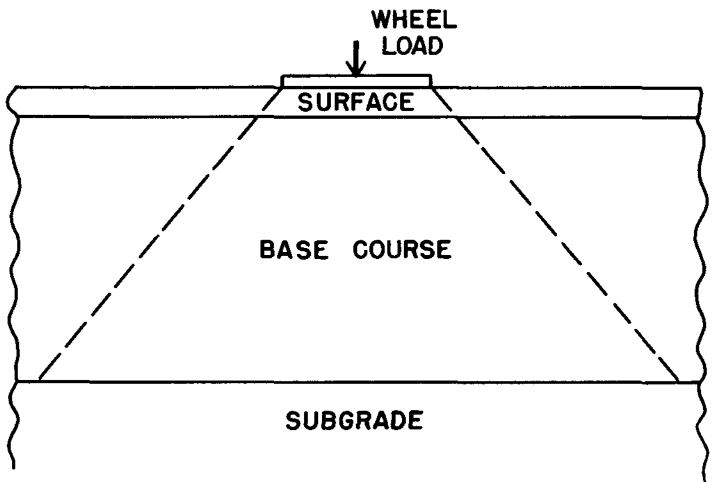


Fig. 1. Distribution of Load Through Flexible Pavement.

The subgrade is normally constructed from the natural soil that occurs on or adjacent to the right-of-way. Since few subgrades have sufficient strength within themselves to support the wheel loads of traffic, they must usually be reinforced by a superimposed base course layer. It is the primary function of the base course to distribute an applied wheel load over such a large area of the subgrade that the bearing capacity of the subgrade is not exceeded, Figure 1. Since the base course must be stable under either wet or dry conditions, it usually consists of gravel, crushed stone, or similar granular aggregates that maintain high strength within themselves when either wet or dry. In some localities, less common substances that are plentiful locally, such as slag, caliche, oyster shell, etc., are used as base course materials. In addition, base courses may be composed of natural sandy soil that has been stabilized by incorporating Portland cement or bituminous binders. They may also consist of black base, and penetration or water-bound macadam.

The principal function of the wearing course is to provide a safe driving surface that is free from dust and mud, and is resistant to the destructive effects of traffic and climate. The wearing course for flexible pavements usually consists of combinations of aggregates with bituminous binders. Depending upon the volume of traffic to be carried, the wearing course may be a surface treatment, penetration macadam, a bituminous mixture, or a combination of two or more of these. When properly designed, bituminous concrete surfaces contribute substantially to the overall load carrying capacity of a flexible pavement.

Because the strength of the subgrade has a great influence on flexible pavement thickness requirements, this paper is divided into two principal divisions. First of all, there is a short section on "Fundamentals of Subgrade Design." This is followed by "Flexible Pavement Thickness Design." It is the second of these two topics to which most of the subject matter of this paper is devoted.

FUNDAMENTALS OF SUBGRADE DESIGN

Apart from the wheel load to be carried, the strength of the subgrade has more influence than any other variable on flexible pavement thickness requirements. For a strong subgrade, the thickness of flexible pavement needed to carry a given wheel load is only a fraction of that required over a weak subgrade. Consequently, in any study of the problem of flexible pavement thickness design, it is important to begin with the subgrade. For this reason, the seven basic principles of subgrade design and construction that are intended to provide a strong subgrade will be reviewed in this section.

All subgrade design and construction procedures should have two basic objectives:

(a) A subgrade that will maintain the highest possible load supporting value throughout the year. The stronger the subgrade can be made, the smaller are the quantities of expensive base course and surfacing materials required.

(b) A subgrade that will undergo a minimum of differential vertical movement during its service life. The smaller this differential vertical movement due to traffic, climate, and other conditions can be made, the smoother-riding the surface of the flexible pavement will be throughout its lifetime.

Since they ordinarily occur on or adjacent to the right-of-way, subgrade soils are usually the cheapest construction materials incorporated into a roadway or runway structure. Consequently, considerable expense for adequate drainage, and for the selection, rejection, special placement, and mechanical manipulation of the soils available, is ordinarily warranted to obtain a finished subgrade of high strength and adequate compaction. From an economic point of view, additional expenditure toward increasing the strength and compaction of the subgrade is usually justified up to the point where it becomes cheaper to utilize base course and surfacing materials to obtain the further wheel load supporting capacity required.

It should be clearly recognized that any failure to develop the inherent strength of the available subgrade soils because of improper or careless design and construction procedures results in a severe economic penalty. The resulting lower subgrade strength requires the use of a greater thickness of expensive base course or surfacing materials, or both, than would otherwise be necessary.

Application of the following seven fundamental principles of subgrade design and construction will provide a strong subgrade subject to minimum differential vertical movement throughout many years of service.

(a) Establish the right-of-way on sandy rather than on clayey soils wherever possible. Clay soils become weak when exposed to water, while sands develop and maintain high supporting value in either the wet or dry condition. For example, to provide runways for the world's heaviest aeroplanes, as much as 75 inches of flexible pavement (base course plus surface) have been laid over a poor clay subgrade soil, whereas only 12 to 15 inches of flexible pavement placed on well compacted sand subgrade soil, will carry the same aircraft.

(b) If there is some choice between sandy and clayey soils for subgrade construction, but the quantities of sandy soils are limited, place the clay and other poorer soils as low in the subgrade as possible, and use the sandy or similar better soils for the top layers of the subgrade.

(c) Provide adequate drainage for surface and sub-soil water that may tend to enter and soften the subgrade, Figure 2. However, it should always be remembered when installing underground drains that capillary water cannot be drained from a soil.

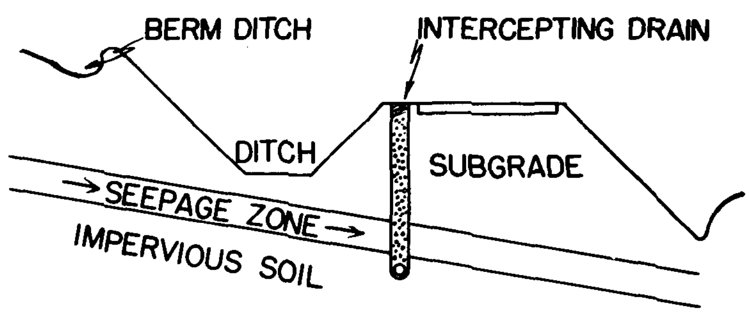


Fig. 2. Adequate Drainage Consists of Intercepting and Removing All Free Surface and Underground Water Which May Damage the Roadway.

(d) Establish the grade line at least four feet above the ground water table, Figure 3. This tends to maintain the upper portion of the subgrade in a drier and stronger condition.

(e) Excavate pockets of frost affected soils, susceptible to acute frost heaving and frost boils, to one-half the depth of frost penetration, but to a minimum depth of two feet, and replace with soils of non-frost heave texture (heavy clays, or free draining sands or gravels), Figure 4.

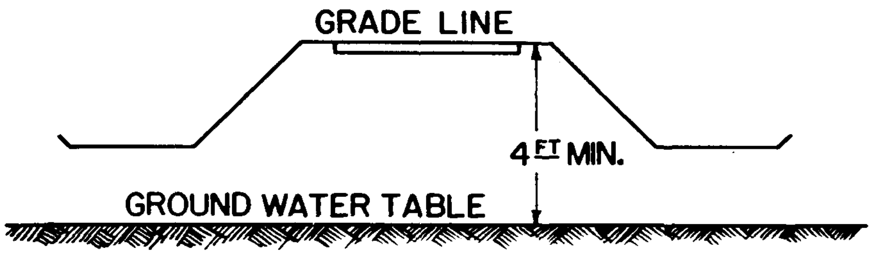


Fig. 3. Maintain the Grade Line at Least 4 Ft. Above the Ground Water Table.

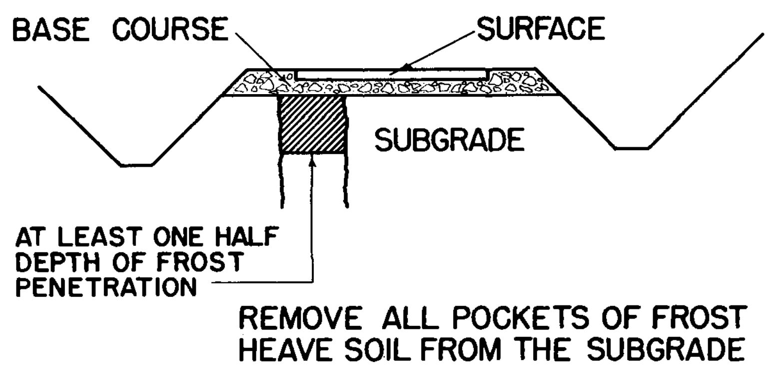


Fig. 4. Pocket of Frost Heave Soil Excavated to at Least One Half Depth of Frost Penetration and Replaced with Non Frost Heave Soil.

(f) Mechanically compact subgrade soils in relatively thin layers at approximately optimum moisture by means of sheepsfoot, pneumatic-tired, or steel-wheeled rollers, for at least the top 12 inches of cut sections, and for the full depth of embankments, Figure 5, to increase their density in place. For airport runways for very heavy aircraft, compaction of cut sections to a depth of several feet is often specified. Mechanical compaction tends to increase subgrade strength, to provide more uniform subgrade bearing capacity, and to reduce differential vertical movement.

(g) Embankments may be carefully constructed within themselves, but may be placed on a foundation soil that is soft and weak. This may cause the embankment to fail by gradually sinking into and displacing the soft soil laterally, or by one or a series of slides. Even if shear failure of the weak underlying soil does not occur, excessive

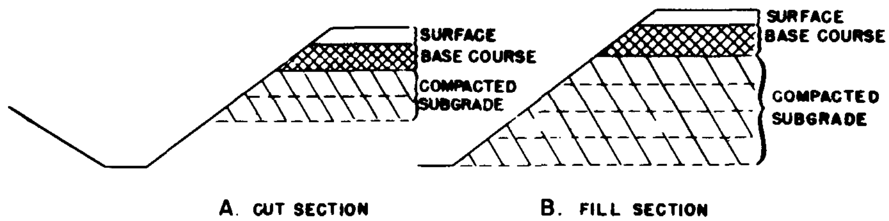


Fig. 5. Diagram Illustrating Degree of Proctor Compaction Required for Cut and Fill Sections.

and uneven settlement will develop as the soft soil consolidates under the weight of the fill.

When the soft foundation soil consists of peat, muck, or other highly organic soils, wherever possible they should be completely removed from under the subgrade embankment, Figure 6, by excavation, displacement, jetting with water, or blasting. Organic soils tend to hold excessive quantities of water, and compress slowly, unevenly, and extensively, over a long period of time. This results in a rough riding surface unless they are removed.

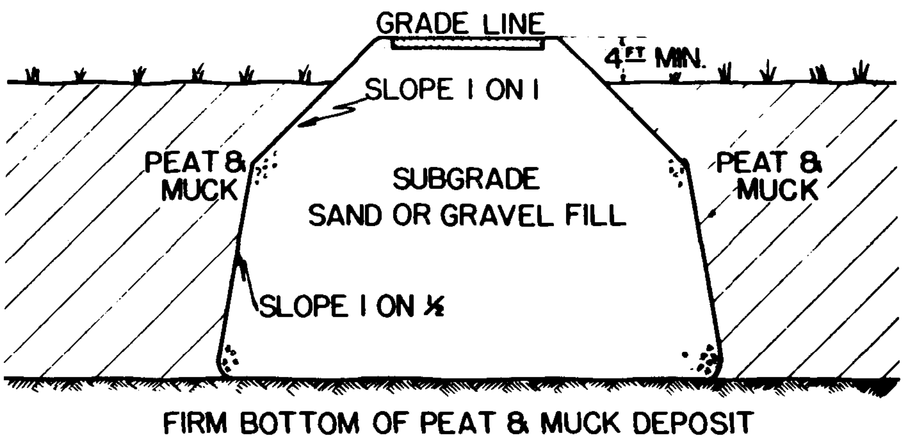


Fig. 6. Remove All Peat and Muck From Under the Subgrade.

If the soft underlying soil is composed largely or wholly of inorganic silt, marl, etc., and cannot be partially or entirely excavated, or completely displaced, its strength can be increased and its settlement speeded up by constructing the embankment in carefully planned stages to avoid overloading the soft soil at any time. Finally, a temporary surcharge may be constructed in the form of an excess depth of embankment, to bring about the desired degree of consolidation of the soft soil more rapidly. Berms may be constructed out from the toe or toes of the embankment to increase stability during consolidation, and on some projects, e.g., the New Jersey Turnpike, sand drains, Figure 7, have been installed to accelerate up both the consolidation of the soft foundation soil, and its increase in strength.

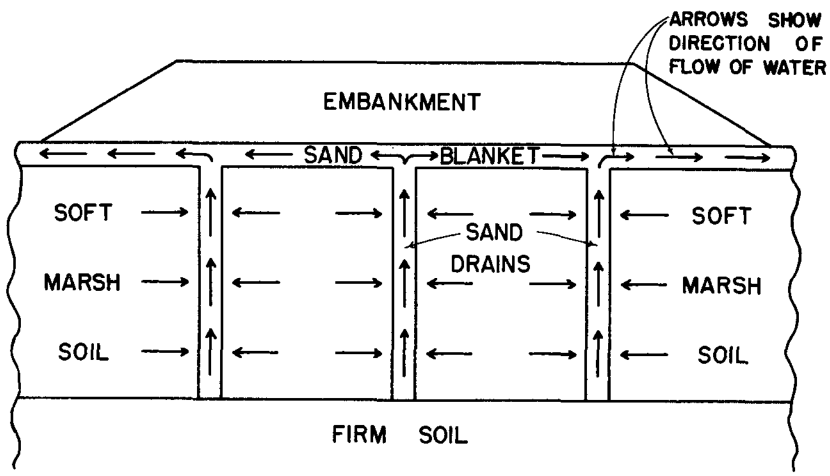


Fig. 7. Vertical Sand Drains Speed up Consolidation of Soft Marsh Soils Under Embankments.

FLEXIBLE PAVEMENT THICKNESS DESIGN

By applying the seven principles of subgrade design just described, a strong well-compacted subgrade will be obtained. The next problem concerns the design of the flexible pavement. Flexible pavement design has two basic objectives:

(a) What is the *minimum* thickness of flexible pavement required to carry any specified wheel load over any given subgrade? Base course and surfacing materials are usually relatively expensive. Consequently, good engineering and economic design both dictate the selection of the *minimum* adequate thickness of flexible pavement that will prevent subgrade failure under the anticipated wheel loads.

(b) The quality (shearing strength) of the base course and surfacing material must be high enough that failure will not occur within the flexible pavement itself.

In this paper, attention will be devoted entirely to the first of these two basic problems, that is, to the required minimum thickness of flexible pavement.

A great many organizations and individuals have studied this problem and have recommended design procedures (1, 2, 3, 4, 5, 6, 7). However, very few of these proposed design methods are supported by data from full scale field tests. The approach to flexible pavement thickness design described in this paper was developed by the Canadian Department of Transport on the basis of many hundreds of repetitive plate bearing tests conducted on actual runways at about forty airports in Canada. This has enabled the load test data to be correlated with observed service performance under known aeroplane traffic. It is because of the writer's close association with the Department of Transport's investigation that their method for determining the required thickness of flexible pavement is described here. It is the design procedure with which the writer is most familiar (8, 9, 10, 11, 12, 13).

Figures 8 and 9 illustrate the types of large weighted tractor trailers employed for load testing during the Canadian Department of Transport's investigation. Measured loads were applied repetitively to steel bearing plates with diameters of 12, 18, 24, 30, 36, and 42 inches, which were placed on the subgrades, base courses, and pavement surfaces of existing runways, Figures 10 and 11. The thicknesses of base course and bituminous surface were carefully measured at each test location.

Subgrade Bearing Capacity

In all cases, the base course and bituminous surface were removed at test locations on existing runways to permit load tests on the subgrade to be conducted. Since the pavements had been in service for a number of years before the subgrade load tests were performed, moisture and density conditions in the subgrade had probably either reached equilibrium, or were closely approaching this condition. Figure 12 provides two very important items of information resulting from a study of the data from load tests made on subgrades.

1. For any given deflection, the supporting value of a subgrade in pounds per square inch can vary over a wide range, depending upon the diameter of the bearing plate employed. For example, Figure 12 shows that at a deflection of 0.2 inch for 10 repetitions of load, for every 1 lb. per square inch supported on a 30-inch diameter bearing plate by a given subgrade, it will carry just over 2 lbs. per square inch on a 12-inch diameter plate, but only about 0.75 lb. per square inch on a 42-inch diameter bearing plate.
2. If the load supported by a subgrade on a given size of bearing plate at a single deflection between 0 and 0.7 inch is known, the load that the subgrade will carry on any other size of bearing plate at any deflection from 0 to 0.7 inch can be found graphically from Figure 12. For example, Figure 12 indicates that for every 1 lb. per square inch that a subgrade will support on a 30-inch diameter bearing plate at 0.2 inch deflection for 10 repetitions of load, it will carry about 3.5 pounds per square inch on a 12-inch plate at 0.5 inch deflection for 10 repetitions of load, or about 0.5 lb. per square inch on a 36-inch diameter bearing plate at 0.1 inch deflection for 10 repetitions of load, etc. Consequently, by means of Figure 12, a vast amount of useful

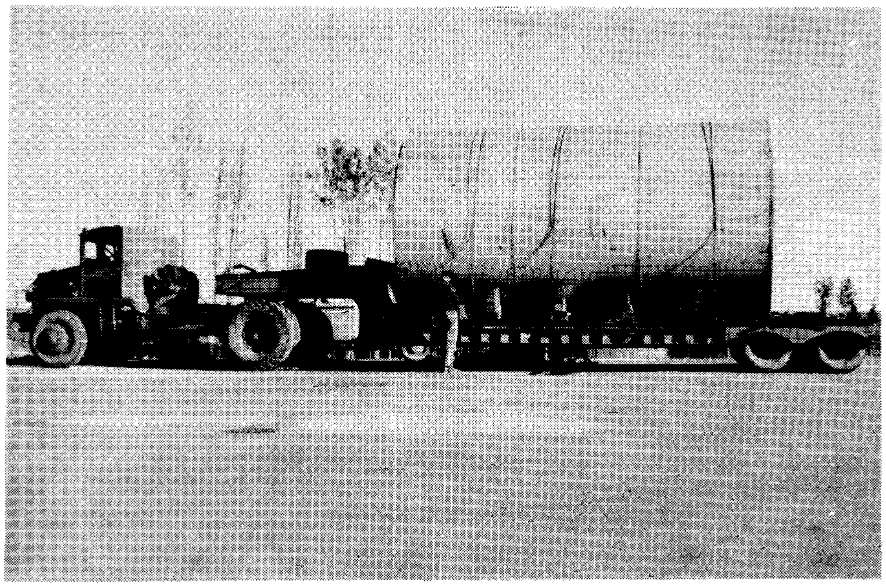


Fig. 8. Load Test Unit No. 1. Capacity 150,000 Pounds.

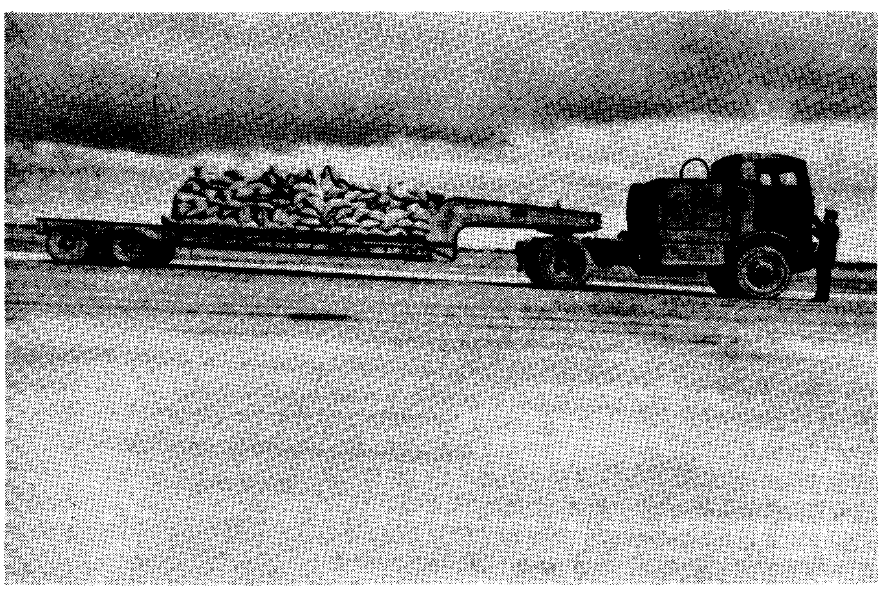


Fig. 9. Load Test Unit No. 2. Capacity 80,000 Pounds.

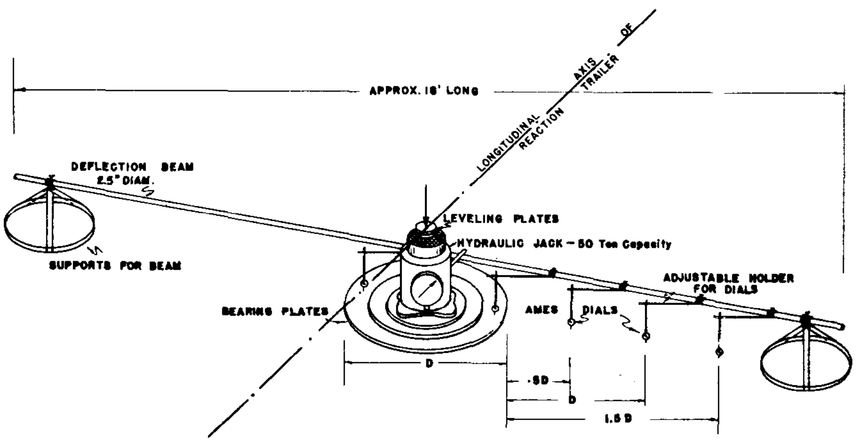


Fig. 10. Diagram Showing Arrangement of Equipment for Bearing Test.

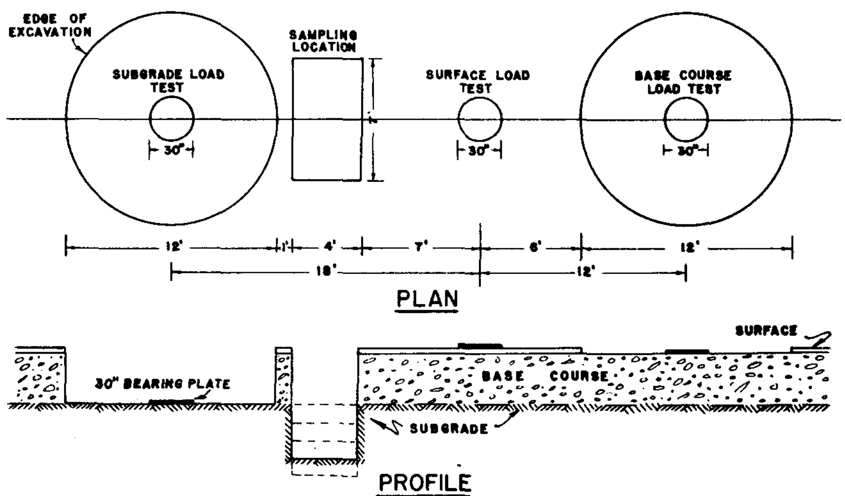


Fig. 11. Diagram Showing Typical Arrangement of Load Tests and Sample Locations.

subgrade bearing capacity information can be obtained from a load test on a single bearing plate for a single deflection. At least this applies to Canadian soils tested so far.

Figure 12 emphasizes a fact that does not seem to be too generally and clearly recognized, namely, that bearing capacity of any single subgrade varies over a very wide range depending upon the size of bearing plate, and upon its deflection under load. Tables of subgrade supporting values that are so frequently published without mentioning either

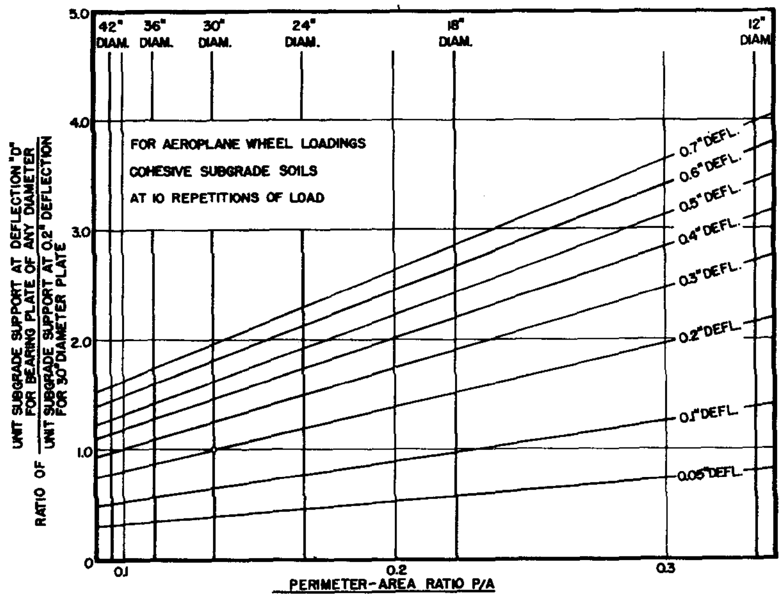


Fig. 12. Ratio of Subgrade Support at Deflection "D" for Bearing Plates of Any Diameter Over Subgrade Support at 0.2" Deflection on 30 Inch Diameter Plate Versus Perimeter Area Ratio.

the size of the loaded area, or the magnitude of the associated deflection, are to a large degree meaningless as a basis for design.

Figure 13 indicates relationships between bearing plate diameter and deflection under load with respect to measured subgrade strength at Canadian airports, on the basis of 1.0 pound per square inch at 0.2 inch deflection for a 12-inch diameter bearing plate. Figure 13 is similar to Figure 12, which is based upon 1.0 pound per square inch at 0.2 inch deflection for a 30-inch diameter bearing plate.

Figure 14 summarizes information from load tests on the surfaces of asphalt pavements, in a manner similar to that of Figure 12 for subgrades, and it is utilized in the same way. Analysis of data from surface plate bearing tests has indicated that flexible pavements are quite similar to subgrade soils insofar as their behaviour under load tests is concerned.

Figure 15 indicates how closely the actual data for a given load test location agree with the straight line relationships between unit load versus perimeter/area ratio of the bearing plates, already illustrated by Figures 12 and 14.

Flexible Pavement Thickness Design Equation

Curves of applied load versus measured deflection were plotted for

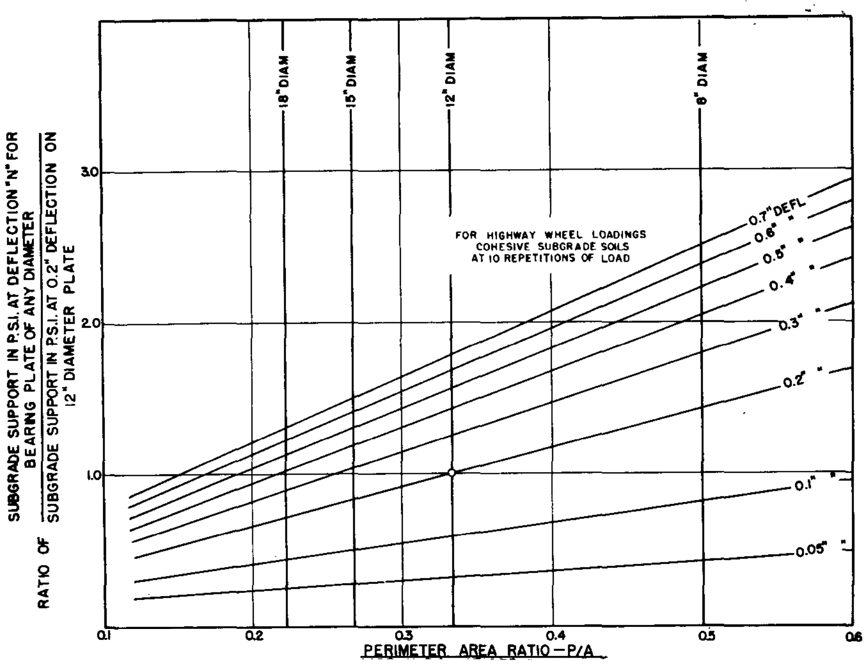


Fig. 13. Ratio of Subgrade Support in P.S.I. at Deflection "N" for Bearing Plate of Any Diameter Over Subgrade Support in P.S.I. at 0.2" Deflection on 12" Diameter Plate Versus Perimeter Area Ratio.

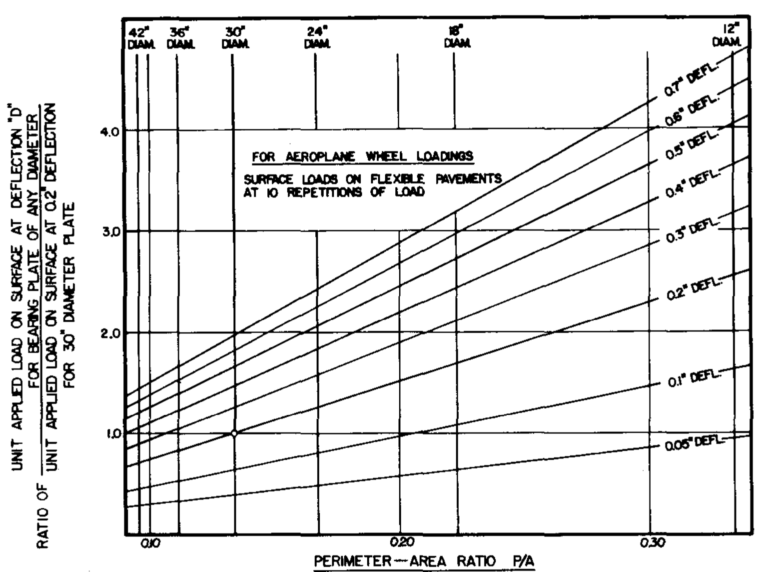


Fig. 14. Ratio of Applied Load on Surface at Deflection "D" for Bearing Plates of Any Diameter Over Applied Load on Surface at 0.2" Deflection on 30" Diameter Plate Versus Perimeter Area Ratio.

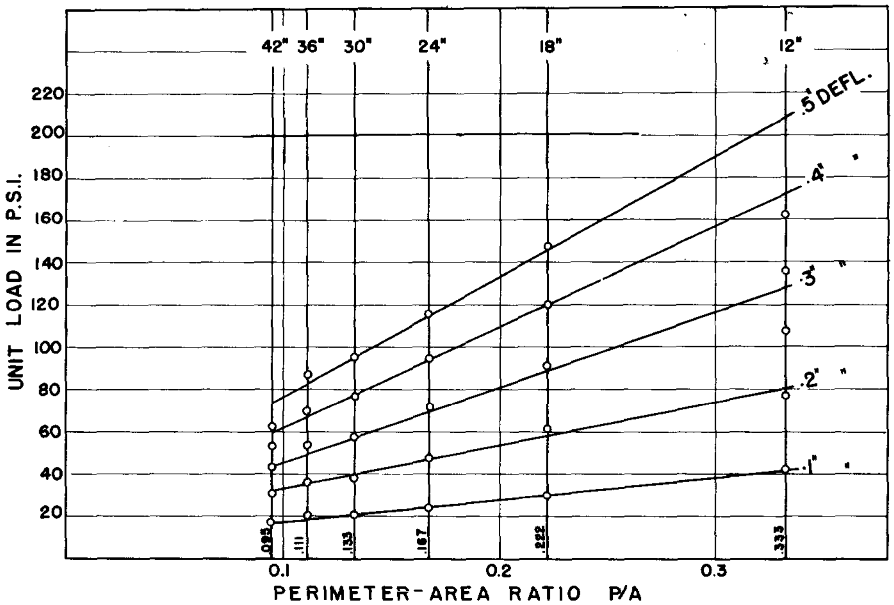


Fig. 15. Influence of Plate Size on Unit Load at Different Deflections.

plate bearing tests on the subgrade, base course, and surface at each test location, as illustrated in Figure 16. The critical deflection for each of the three layers was taken as 0.5 inch for 10 repetitions of load for airport pavement design, and as 0.2 inch for 10 repetitions of load for flexible pavements for highways. These critical deflections provide plate bearing values that appear to correlate best with the actual wheel loads of unlimited traffic that can be supported by flexible pavements without failure in each case.

Measurements of the thickness of base course and bituminous surfacing, and load test data like those of Figure 16, were obtained at each test location. When similar data from hundreds of test locations were analysed as described elsewhere (8), they indicated that the minimum thickness of granular material required to carry any specified wheel load over any given subgrade is provided by the following simple design formula,

$$T = K \log \frac{P}{S}$$

where T = required thickness of granular material in inches
P = gross single wheel load to be carried on runway or highway
S = subgrade support at the same deflection and for the same contact area that pertain to P
K = the base course constant, which is an inverse measure of the supporting value of the base course per unit thickness.

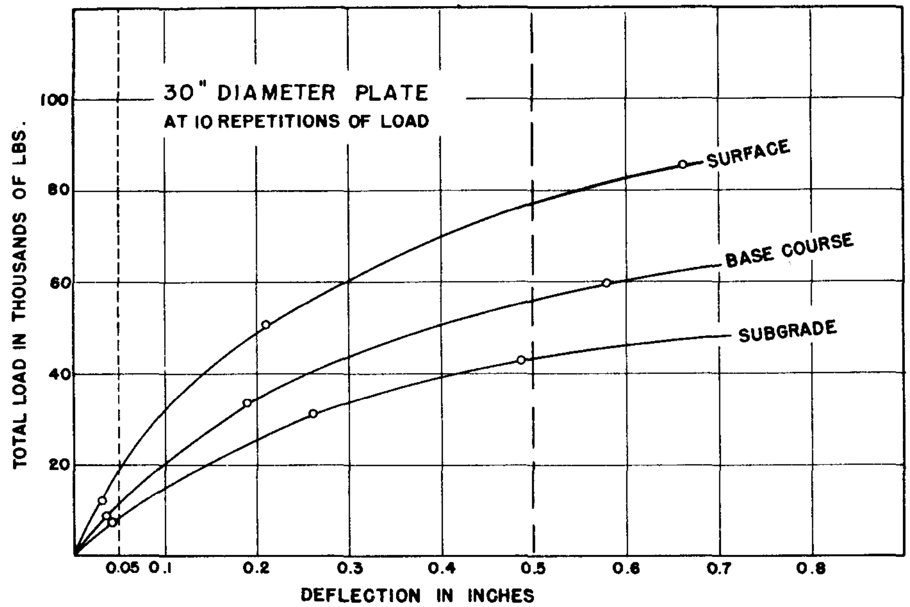


Fig. 16. Load Versus Deflection Curves (Normal) for Subgrade, Base Course and Surface.

The Base Course Constant K

The base course constant K has been evaluated by analysing subgrade and base course load test data and the corresponding base course thickness measurement at each of many test locations, (8, 9). The value of the base course constant K varies with the diameter of the bearing plate as illustrated in Figure 17, but appears to be essentially independent of the type of granular base course material. It is known that for any given size of contact area or bearing plate diameter, the value of K must be increased when the thickness of the granular base becomes great (8). However, for the range of thicknesses *ordinarily* required for highway and airport wheel loadings, the values of K given by Figure 17 seem to be satisfactory.

It is true that various types of base course aggregates can be made to show quite different strengths or stabilities in laboratory tests. However, as base courses are currently constructed, there is considerable doubt that these granular materials develop similar differences under service in the field. Laboratory tests demonstrate that the stability of a granular aggregate depends not only upon the angularity and surface texture of the particles, but also upon the density imparted to the aggregate by compaction. On the other hand, the angularity of shape and roughness of particle surface texture that lead to high stability, also provide considerable resistance to compaction to high density. Consequently, it appears that our present base course compaction methods

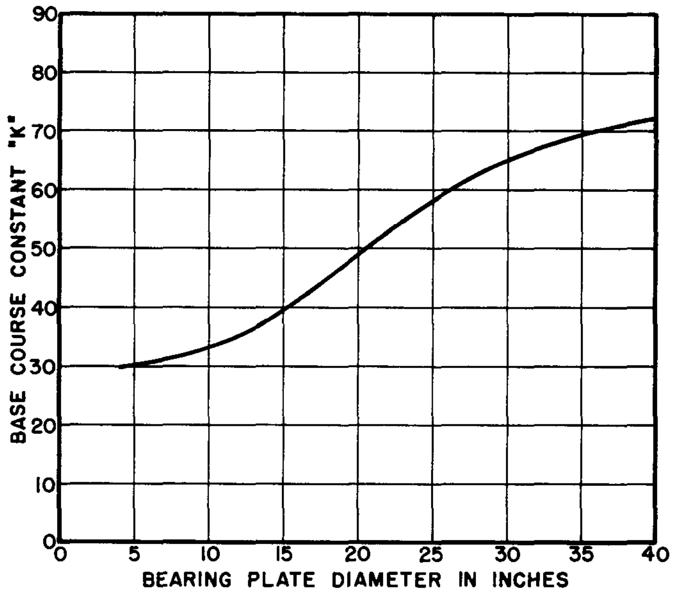


Fig. 17. Influence of Bearing Plate Diameter on Value of "K" in Flexible Pavement Design Equation T = K Log P/S.

are unable to compact angular aggregates with rough surface textures as to high relative density as the more rounded aggregates. As a result there seems to be little difference in their load transmission characteristics in the field. The higher relative densities of the more rounded aggregates seem to compensate for the greater angularity but lower relative densities of the more highly crushed aggregates, so that base courses made with both types of aggregate seem to provide approximately the same supporting value per unit thickness in the field. At least, this conclusion is indicated by an analysis of the data from the many hundreds of load tests that have been conducted during the Department of Transport's investigations of airport runways in actual service. It should be emphasized that these load tests have been performed on actual airport runways that have been in service for a period of years, and not on specially constructed and unseasoned test sections.

If by means of new equipment, the vibratory type for example, and new compaction procedures, highly crushed aggregates of angular shape and rough surface texture could be compacted to the same high relative density as the more rounded aggregates, and if these relative density characteristics can be retained in service, base courses made with these highly crushed aggregates would be expected to have superior load transmission characteristics.

In the meantime, analysis of the Department of Transport's load tests indicate that the supporting values per unit thickness of base courses made from pit-run and crusher-run gravels, crushed stone, and the various mechanically stabilized aggregates, must be considered essentially equal. It is true that the load test data have shown that base courses made with any one of these aggregate materials occasionally show higher than average supporting value per unit thickness, but they are not consistent in this respect. Consequently, in view of the manner in which granular base courses seem to be constructed at the present time, or at least in view of their performance under load tests after several years in service, a reasonably conservative approach to flexible pavement design makes it necessary to assign the same supporting value per unit thickness to granular base courses, regardless of the aggregate type employed for their construction. This in turn implies that the value of the base course constant K is independent of the type of granular base course material, but varies with the size of loaded area, Figure 17.

The Department of Transport's plate bearing tests indicate that one inch of properly designed and constructed bituminous concrete has the supporting value of at least one and one-half inches of granular base course material. This ratio appears to be quite conservative. Consequently, the value of the base course constant K for well designed and constructed bituminous concrete, is two-thirds of its corresponding value for granular base course material. (The base course constant K provides an *inverse* measure of the supporting value of the base course per inch of thickness.)

Flexible Pavement Thickness Design Charts for Unlimited Traffic

On the basis of the design equation, $T = K \log (P/S)$, charts of curves can be prepared which show the minimum thickness of granular material needed to carry any given wheel load over any specified subgrade. Figure 18 illustrates this chart of curves for the design of airport runways, taxiways, and aprons, while the curves of Figure 19 indicate the thickness requirements of flexible pavements for highway loadings.

Figures 18 and 19 are very easy to use. Suppose, for example, that a flexible pavement for a highway is to be designed for a single wheel load of 12,000 pounds, and that the measured supporting value of a subgrade is 4,000 pounds on a 12-inch diameter bearing plate at 0.2 inch deflection for 10 repetitions of load. What minimum thickness of granular base course material is required? Along the top of Figure 19 locate the ordinate indicating a subgrade supporting value of 4,000 pounds on a 12-inch diameter bearing plate at 0.2 inch deflection for 10 repetitions of load. Proceed vertically down this ordinate to its intersection with the curve representing a wheel load of 12,000 pounds. From this point of intersection continue horizontally to the left hand margin and read off the thickness indicated. In this case the required thickness of granular material is 16 inches. If the wearing course were to consist of a thin bituminous surface treatment, the thickness of granular base course required would be 16 inches. On the other hand, if a well-

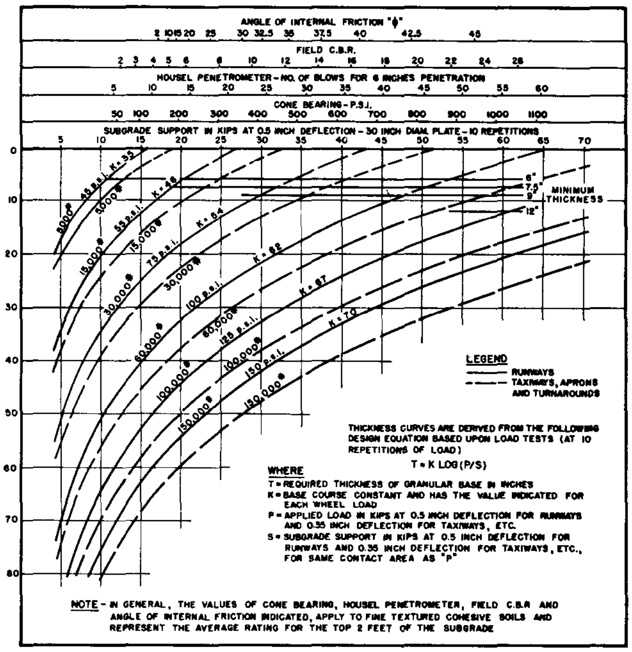


Fig. 18. Design Curves for Flexible Pavements for Runways and Taxiways, etc., for Aeroplane Wheel Loadings (Full Load on Single Tire).

designed asphaltic concrete surface course 3 inches thick were specified, and if 1 inch of asphaltic concrete were considered equivalent in supporting value to 1.5 inches of granular base, then 3 inches of asphaltic concrete would be equivalent to 4.5 inches of granular base in supporting value, and only 11.5 inches of granular base would be required. Consequently, this flexible pavement thickness problem and its solution can be briefly summarized as follows:

<u>Given</u>

Single Wheel Load - 12,000 pounds
Traffic - unlimited
Subgrade Support - 4,000 pounds on a 12-inch diameter bearing plate at 0.2 inch deflection for 10 repetitions of load

<u>Solution</u>

(a) When the wearing course is to consist of a thin bituminous surface treatment, from Figure 19,
Required thickness of granular base course - 16 inches.

(b) When the wearing course is to consist of a 3-inch thickness of well-designed asphaltic concrete, the flexible pavement thickness requirements are:

Thickness of Granular Base	-	11.5 inches
Thickness of Asphaltic Concrete	-	3.0 inches
Total Thickness		14.5 inches

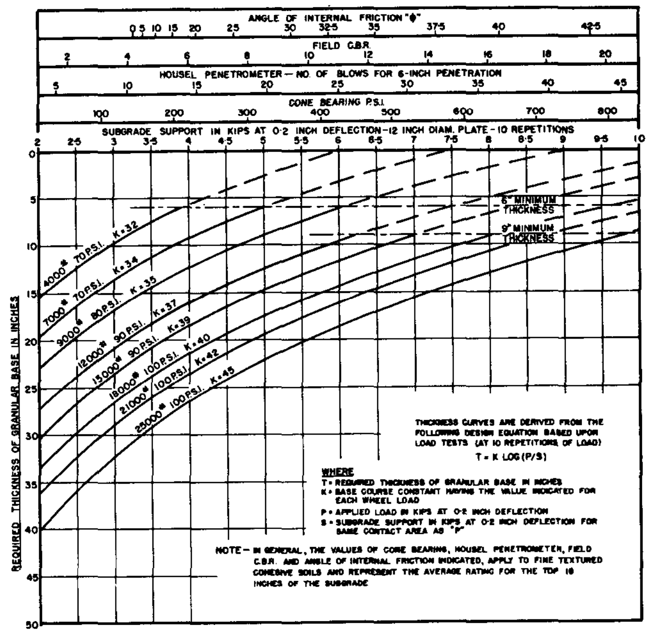


Fig. 19. Design Curves for Flexible Pavements for Highway Wheel Loadings for Highest Traffic Capacity (Single Wheel).

Since the different variables on which the required thickness of a flexible pavement depends cannot be evaluated precisely, base course thickness requirements should be carried to the next full inch. The design of the flexible pavement, therefore, becomes:

Thickness of Granular Base	-	12 inches
Thickness of Asphaltic Concrete	-	3 inches
Total Thickness		15 inches

Verification of the Flexible Pavement Design Equation

The supporting value of the pavement, P, the subgrade supporting value, S, and the overall thickness of base course and surface, T, were measured at test locations at a considerable number of airports, and the base course constant K has been evaluated for various bearing plate sizes, Figure 17. Consequently, both measured and calculated data are available for checking the accuracy of the design equation, $T = K \log (P/S)$, to determine how closely it represents the actual data, and whether it is likely to lead to either serious overdesign or underdesign. Measured values of P are provided by plate bearing tests on the finished pavement. Calculated values of P are obtained by substituting K values from Figure 17 and measured values for S and T in the design equation, $T = K \log (P/S)$, and calculating P, which is the only unknown. Calculated and measured values of P can then be compared.

In Figure 20, a comparison between calculated and measured values for P is presented for over two hundred test locations at 16 airports for which the necessary test data have been obtained. It should be particularly noted that the data of Figure 20 cover measured pavement supporting values ranging from about 10,000 pounds to over 100,000 pounds; that is, from quite weak to very strong runways. The actual flexible pavement thicknesses (base course plus asphalt surface) to which the data of Figure 20 pertain, varied from about 5 to about 30 inches.

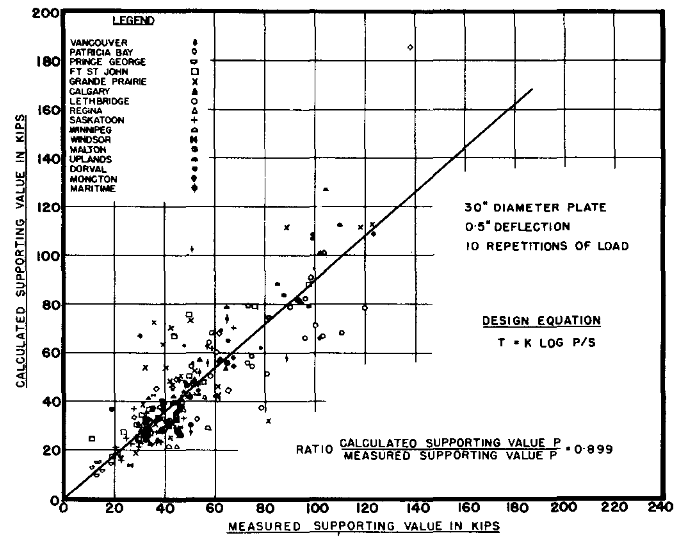


Fig. 20. Measured Runway Supporting Value Versus the Supporting Value Calculated by Means of the Flexible Pavement Design Equation for the Sixteen Airports for Which These Data Are Available.

While there is some scattering of data in Figure 20, this is to be expected for at least two reasons. First, at each test site on a runway, the plate bearing test on the subgrade was made at a distance of from 10 to 18 feet from the load tests on the base course and on the pavement surface, in order that the former would not be influenced by the latter. As anyone familiar with soil testing is aware, noticeable differences in subgrade bearing capacity sometimes occur over this distance, even for subgrades that appear to be homogeneous. Secondly, the thicknesses of base course and surface were measured at the excavation made for the subgrade load test, and these were assumed to apply at the locations of the corresponding base course and surface load tests. However, some variation in these thicknesses was possible over the 10 to 18 feet separating the subgrade and base course and surface load test locations. In view of these factors, the scattering of data in Figure 20 is not excessive, and is probably less than might have been anticipated.

The best line through the data of Figure 20 was established by the method of least squares, and provides an average ratio of 0.899 for calculated versus measured values of P. This ratio indicates that on the average, the design equation leads to 10 per cent overdesign, and therefore is slightly conservative. Consequently, Figure 20 provides verification of the accuracy and utility of the design equation, $T = K \log (P/S)$, for determining the required thickness of flexible pavements.

Flexible Pavement Thickness Requirements for Stationary Wheel Loads

Airport runways are designed to support moving wheel loads, except for the turnaround areas at each end. In general, rural highways and city streets should also be designed to carry moving wheel loads.

Airport operating experience has demonstrated that other factors being equal, a greater thickness of flexible pavement is required for taxiways, aprons, and the turnaround areas at the end of runways, where aircraft are stationary or moving slowly, than for runways that must support capacity operations of the same aircraft that are moving rapidly. This is illustrated in Figure 18, where the flexible pavement thickness requirements for taxiways, aprons, and the turnaround areas at the ends of runways, are represented by broken line curves, and those for runways for capacity operations, by solid line curves. For any given wheel load, it will be noted that a smaller thickness of flexible pavement is indicated for runways for capacity operations than for taxiways, aprons, etc.

The curves for flexible pavement thickness requirements for runways shown in Figure 18, are based upon the strength of the subgrade at 0.5 inch deflection (30-inch diameter bearing plate, 10 repetitions of load), while those for the thickness requirements for taxiways, aprons, etc., are based upon the supporting value of the subgrade at 0.35 inch deflection (30-inch diameter bearing plate, 10 repetitions of load). Both sets of curves (broken and solid lines) can be shown on the same diagram, Figure 18, because it has been demonstrated that for Canadian soils tested so far at least, the load supported by the subgrade at 0.35 inch deflection is a definite fraction of the load supported at 0.5 inch deflection, when the bearing plate diameter and number of repetitions of load are identical (9).

The design criteria for taxiways, aprons, etc., at airports, can be employed to establish the thicknesses of flexible pavements required for parking areas, loading and unloading areas, etc., where highway vehicles are stationary for a time. On this basis, Figure 21 provides a chart of curves for this purpose. The curves in Figure 21 are actually based on the supporting value of the subgrade at 0.35 inch deflection (12-inch diameter bearing plate, 10 repetitions of load), although the abscissa for Figure 21 is shown in terms of subgrade strength at 0.2-inch deflection (12-inch diameter bearing plate, 10 repetitions of load). This arrangement is possible because the subgrade support at 0.2 inch deflection is a definite fraction of the subgrade support at 0.35 inch

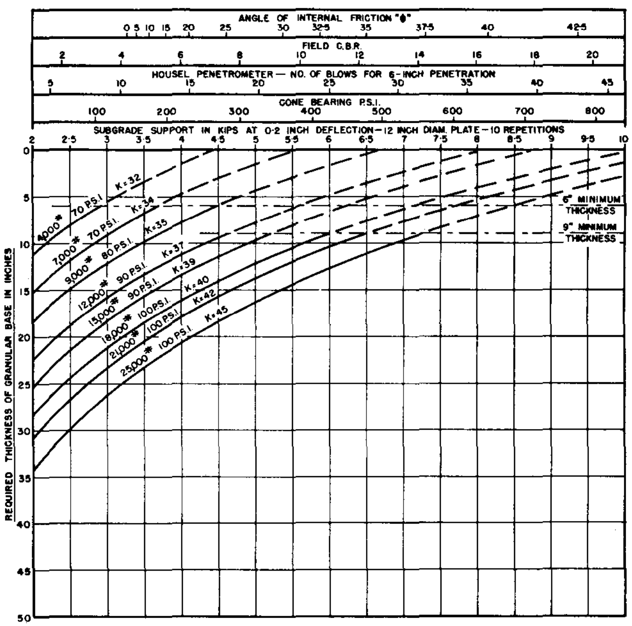


Fig. 21. Flexible Pavement Thickness Requirements for Parking Areas, etc., Subjected to Stationary Wheel Loads (Single Wheel).

deflection, for the same bearing plate diameter and number of repetitions of load (9). By employing subgrade support at 0.2 inch deflection, for a 12-inch diameter bearing plate and 10 repetitions of load, for both Figures 19 and 21, a direct comparison can be made between flexible pavement thickness requirements for capacity traffic volume of moving highway wheel loads, Figure 19, versus those for stationary highway wheel loads of the same weight, Figure 21.

It will be noted that for any specified value of subgrade support, the flexible pavement thickness requirements indicated by Figure 21 for any given stationary highway wheel load, are somewhat less than those of Figure 19 for capacity traffic volume of the same highway wheel load. Experience has shown that for the large number of repetitions of any given wheel load applied in the form of capacity traffic volume on highways, a greater thickness of flexible pavement is required than for a parking area where the same highway wheel load is stationary.

It will be observed from Figure 18, that in the case of airports, flexible pavement thickness requirements for runways for moving aeroplane wheel loads are *less* than those for taxiways, aprons, etc., for stationary aircraft wheel loads. For highway wheel loads on the other hand, Figures 19 and 21 indicate that a *greater* thickness of flexible pavement is needed for highways for capacity traffic volume of moving wheel loads than for parking areas for stationary wheel loads of the same weight. This reversal of the order of thickness requirements between airports and highways for moving versus stationary wheel loads, is explained by the fact that capacity traffic volumes on highways represent from 20 to 30 times as many vehicles as capacity aircraft traffic on runways over any given period of one week, one month, one year, etc. In addition, aircraft traffic is spread over at least one-third of the width of a runway which is usually from 150 to 200 feet wide, whereas highway traffic is confined within a traffic lane from 10 to 12 feet wide, and the actual wheel paths within each traffic lane on which the wheel loads are concentrated are about 3 to 4 feet in width. Consequently, a flexible pavement subjected to capacity traffic on a highway receives a very much higher concentration of wheel loads than a runway that is carrying capacity aircraft traffic.

Other Factors Influence Flexible Pavement Thickness Requirements

Figures 18 and 19 are basic design charts for flexible pavement thickness requirements. However, they could be applied only under the standard conditions of (a) wheel loads on single tires, (b) unlimited traffic (capacity traffic volumes), and (c) uniform subgrade strength throughout the year.

Having established flexible pavement thickness requirements for certain standard conditions, Figures 18 and 19, it becomes necessary to consider the modifications in these thickness values that must be made when conditions are not standard. Some of the more common factors that may modify the flexible pavement thickness requirements indicated by Figures 18 and 19 are:

1. wheel load impact,
2. substitution of dual, dual tandem, or other multiple wheel arrangements for single wheels on aircraft,
3. substitution of duals for single wheels on highway vehicles,
4. eccentricity of axle loadings,
5. tandem axle spacings on trucks,
6. traffic volume,
7. frost action and climate,
8. braking stresses,
9. quality of base course material,
10. greater thicknesses of bituminous pavement,
11. paved shoulders.

The effect of each of these factors on flexible pavement thickness requirements will now be considered.

Influence of Wheel Load Impact

In a section on "Load Shift," the W.A.S.H.O. Test Road report (14) points out that the load on any wheel of the moving test vehicle increased and decreased several times a second, and that a pavement designed for a normal static wheel load of 11,200 pounds would be subjected during these very short periods to wheel loads of as much as 13,000 pounds or higher.

In spite of this, the writer believes that flexible pavements for highways should be designed for normal static wheel loads, and that no allowance is required for the impact developed by moving vehicles. This view is supported by the fact that no increase in flexible pavement thickness, because of impact, is made when designing flexible pavements for airport runways, even though various methods of measurement have indicated that stresses ranging from one and one half to more than four times the static weight of an aircraft may be exerted on the struts of the landing wheel assembly at touchdown. Furthermore, these high impact loadings when landing may be of several seconds' duration. Although impact stresses of this magnitude are developed by aircraft when landing on runways, service records justify the selection of smaller thicknesses of flexible pavement for runways, than for the taxiways, ends of runways, and aprons, where aircraft are stationary or move very slowly.

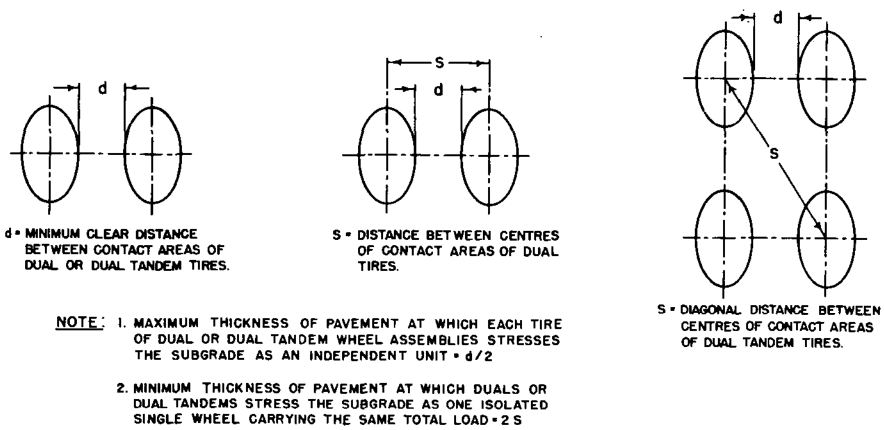
The W.A.S.H.O. Test Road report (14) indicates that the load on any wheel increases and decreases several times a second. It is well known that most materials develop much higher strengths when loaded rapidly. It is doubtful, therefore, that momentary increases in a rapidly moving highway wheel load of up to fifteen or twenty per cent require any increase in flexible pavement thickness requirements for highways above that for the normal static wheel loading. As a matter of fact, if an impact factor is needed, it is believed that it has been already included in the thickness requirements shown in Figure 19. While the curves of Figure 19 are based upon an equation of design, $T = K \log \frac{P}{S}$, this is merely a mathematical device for expressing the thickness requirements that field experience has shown to be necessary *for moving wheel loads* on rural highways carrying unlimited traffic.

On the other hand, if a very conservative approach to flexible pavement thickness requirements is being adopted by the designer, increasing the normal static wheel load by 15 per cent would seem to make ample provision for the impact factor. On this basis, if the normal static wheel load is 9,000 pounds, the design wheel load after including a 15 per cent impact factor, would be 10,500 pounds.

Effect of Multiple Wheels on Aircraft Landing Gear

Figures 22 and 23 illustrate a method proposed by the Corps of Engineers (15) for determining the reduction in flexible pavement thickness for airport runways that can be made if the gross weight of an aircraft is supported on a dual or dual tandem wheel assembly rather than on a single wheel. This method is based on evidence from soil mechanics, that for the same critical pressure transmitted to the subgrade, a smaller thickness of flexible pavement can be employed if a given total load is carried on duals or dual tandem wheels rather than on a single tire.

Suppose for example that 60,000 pounds is the total load to be carried



(a) (b) (c)

Fig. 22. Diagram Illustrating Dimensions of Contact Areas That Control Thicknesses of Pavements at Which Dual or Multiple Wheel Assemblies Stress the Subgrade as Independent Units and as One Isolated Single Wheel Carrying the Same Total Load.

on the wheel assembly. The load on a single wheel becomes 60,000 pounds in this case. However, the load on *each* member of the two dual wheels is only 30,000 pounds. It is obvious that if the spacing between the duals is wide enough, a flexible pavement that would support 30,000 pounds on an isolated single wheel would carry 60,000 pounds on the duals, the tire inflation pressures being the same. The critical thickness of flexible pavement at which this occurs is $\frac{d}{2}$, Figure 22(a), where d is the clear spacing *between the contact areas of the duals*. The same reasoning applies in the case of dual tandems, except that when the spacing between the individual wheels is wide enough, a flexible pavement that would carry 15,000 pounds on a single wheel would support 60,000 pounds on the dual tandem arrangement, Figure 22(c).

At the other extreme, there is a thickness of flexible pavement at which the pressure transmitted to the subgrade is the same regardless of whether the load of 60,000 pounds is carried on a single wheel or on a multiple wheel assembly. This critical depth of flexible pavement is 2S, Figure 22(b) and (c), where S is the distance between the centres of the contact areas of duals, Figure 22(b), but is the diagonal distance between the centres of the contact areas of dual tandems, Figure 22(c).

For purposes of design, the load on a multiple wheel assembly must be converted first to an "equivalent single wheel load." If a flexible pavement is just strong enough to support a given load on a multiple wheel arrangement, the load must usually be reduced if it is to be carried on a single wheel on the same pavement structure without causing failure. Consequently, the "equivalent single wheel load" is normally

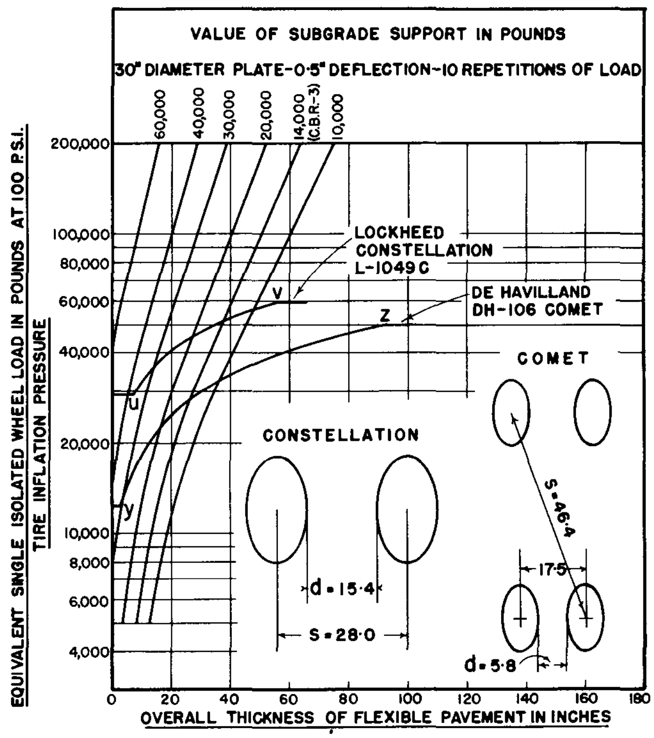


Fig. 23. Flexible Pavement Design and Evaluation Chart for Single Wheel and Multiple Wheel Landing Gear Assemblies (Tire Inflation Pressure 100 P.S.I.).

smaller than that applied to a multiple wheel assembly. Therefore, flexible pavement thicknesses that are just adequate for carrying 60,000 pounds, for example, on a multiple wheel arrangement will support "equivalent single wheel loads" somewhere between 30,000 to 60,000 pounds in the case of duals, and within the range of 15,000 to 60,000 pounds in the case of dual tandems, depending upon the actual thickness in each case. This is illustrated in Figure 23.

Figure 23 provides the same general design information as Figure 18, but it is arranged in a somewhat different manner. The ordinate of Figure 23 is load on a single wheel in pounds, the abscissa is required thickness of flexible pavement in inches, while each curve represents a given value of subgrade strength in pounds as measured by a 30-inch diameter bearing plate at 0.5 inch deflection for 10 repetitions of load. Figure 23 is restricted to a tire inflation pressure of 100 p.s.i.

Consider first the Constellation L-1049C aeroplane, which applies a load of 59,000 pounds to the dual wheel assembly on each leg of the main landing gear. Since d = 15.4 inches, $\frac{d}{2}$ = 7.7 inches. Also S = 28 inches, and 2S = 56 inches. Consequently, a flexible pavement 7.7 inches thick that will support 29,500 pounds on an isolated single wheel will carry the Constellation's 59,000 pounds on duals.

Figure 23 indicates that a flexible pavement 7.7 inches thick will support a single wheel load of 29,500 pounds if the subgrade supporting value is at least 36,000 pounds on a 30-inch diameter bearing plate at 0.5 inch deflection for 10 repetitions of load, point u. The equivalent single wheel load of the Constellation's dual wheel loading of 59,000 pounds under these conditions is 29,500 pounds. Similarly, at a flexible pavement thickness of 56 inches, the equivalent single wheel load is 59,000 pounds, point v. Join points u and v by a curved line. The precise position of this curve in Figure 23 can be easily established because it is a straight line when the logarithm of equivalent wheel load is plotted versus the logarithm of flexible pavement thickness. uv is curved in Figure 23 because it is a semi-log diagram of equivalent single wheel load versus thickness.

The curved line uv in Figure 23 provides the equivalent single wheel load for the Constellation's dual wheel load of 59,000 pounds for all flexible pavement thicknesses between 7.7 and 56 inches. Conversely, the curved line uv indicates the thicknesses of flexible pavement that are needed to carry the Constellation's 59,000 pounds on dual wheels over subgrades of different supporting values.

By comparing the thickness of flexible pavement required to carry a single wheel load of 59,000 pounds over any given subgrade, with the thickness indicated by the curved line uv for the same subgrade, the decrease in thickness due to the use of dual wheels can be determined. For example, when the subgrade support is 20,000 pounds on a 30-inch diameter plate at 0.5 inch deflection for 10 repetitions of load, the uv curve of Figure 23 indicates that the Constellation's wheel load of 59,000 pounds on duals corresponds to an equivalent single wheel load of 46,600 pounds, and requires a flexible pavement thickness of 28 inches. On the other hand, for a load of 59,000 pounds on a single wheel on the same subgrade, Figure 23 indicates that 32.5 inches of flexible pavement are necessary. In this case, therefore, the use of duals reduces the thickness requirement by 4.5 inches or by about 14 per cent.

The data illustrated in Figure 23 demonstrate that dual wheels on aircraft landing gear decrease flexible pavement thickness requirements by from about 5 per cent on weak subgrades to about 35 per cent on strong subgrades.

The DeHaviland DH-106 Comet employed a dual tandem wheel assembly, Figure 23, to support a load of 50,000 pounds. The distance between the centres of the two forward wheels of the dual tandem arrangement is 17.5 inches, and for the two rear wheels is 14.25 inches. At a tire inflation pressure of 100 p.s.i., this results in a clear spacing d = 5.8 inches between the two rear wheels, Figure 23. The distance between bogies (axles) of the dual tandem is 43.6 inches, from which it can be calculated that S = 46.4 inches (Figure 23). Because the dual tandem wheel assembly supports 50,000 pounds, this results in a load of 12,500 pounds on each of the four wheels.

Since d = 5.8 inches, $\frac{d}{2}$ = 2.9 inches, and as explained above in the case of the Constellation, a flexible pavement 2.9 inches thick, capable of supporting a single wheel load of 12,500 pounds, point "y" in Figure 23, would carry 50,000 pounds on the Comet's dual tandem wheel assembly. Also, at a depth of 2S = 92.8 inches, point "z" in Figure 23, it makes no difference insofar as flexible pavement thickness requirements are concerned, whether the load of 50,000 pounds is applied to the dual tandem wheel assembly, or to a single wheel. The points "y" and "z" are joined by a curve that is a straight line on a log-log plot of equivalent single wheel load versus flexible pavement thickness. For each value of subgrade support, the curve yz indicates the thickness of flexible pavement required for capacity operations of the Comet's wheel load of 50,000 pounds on dual tandems, and also gives the corresponding equivalent single wheel load. For example, for a subgrade support of 10,000 pounds on a 30-inch diameter bearing plate at 0.5 inch deflection for 10 repetitions of load, a flexible pavement thickness of 39 inches, (intersection of yz curve with the curve representing a subgrade support of 10,000 pounds), will support the Comet's 50,000 pounds on dual tandems, and the corresponding single wheel load is 39,000 pounds. For capacity operations of a single wheel load of 50,000 pounds, and the same subgrade, a flexible pavement thickness of 47 inches would be needed. In this case therefore, the dual tandem wheel assembly permits a decrease of 8 inches in thickness, a thickness reduction of about 17 per cent.

A study of the curve yz in Figure 23, indicates that when aircraft are equipped with dual tandem wheel assemblies instead of single wheels, flexible pavement thickness requirements can be reduced by from about 15 per cent on very weak subgrades, to about 50 per cent on very strong subgrades.

Figures 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, and 36,* are similar to Figure 23, but provide flexible pavement thickness design curves for tire inflation pressures of 80, 90, 100, 110, 120, 130, 140, 160, 180, 200, 225, 250, and 300 p.s.i. By means of Figures 24 to 36, and by using the procedure illustrated by Figures 22 and 23, flexible pavement thickness requirements, and corresponding equivalent single wheel loads, can be determined for aircraft multiple landing wheel assemblies of any configuration, and for tire inflation pressures over the range from 80 to 300 p.s.i.

For any *given* spacing or configuration of the wheels on aircraft landing gear, it is a simple matter to prepare flexible pavement design charts from which the required thickness of flexible pavement can be read directly. Figures 37 and 38 are examples of these charts for dual wheels with centre to centre spacings of 30 inches, and tire inflation pressures of 100 and 200 p.s.i., respectively. Figures 39 and 40 are similar design charts for dual tandem wheel assemblies for which the

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*To preserve the continuity of this paper, Figures 24 through 40 have been printed as an appendix at the end of this paper.

centre to centre spacing of the duals is 30 inches, while the spacing between bogies (axles) is 50 inches.

It is a serious disadvantage of Figures 37, 38, 39, and 40, that they can be used without error only for the wheel spacings and configurations, and for the tire inflation pressures shown. For aircraft with wider spacings between the duals and bogies, or with smaller tire inflation pressures than indicated, use of Figures 37 to 40 would result in overdesign. Conversely, for aircraft with narrower centre to centre spacings of the duals, or with shorter distances between bogies, or with higher tire inflation pressures than shown, use of Figures 37 to 40 would lead to underdesign of the flexible pavement thickness requirement.

It would be a time consuming task to prepare flexible pavement thickness design charts like those of Figures 37 to 40 for the many different multiple wheel spacings and arrangements, and for the wide range in tire inflation pressures now employed for commercial and military aircraft. Consequently, design charts like those of Figures 37 to 40 are of very limited usefulness.

On the other hand, as previously pointed out, by employing the procedure illustrated by Figures 22 and 23, and applying it to Figures 24 to 36, flexible pavement thickness requirements can be easily and quickly determined for aircraft multiple wheel landing gear assemblies of any configuration, and for any tire inflation pressure over the entire range from 80 to 300 p.s.i.

Influence of Dual Wheels on Highway Vehicles

The procedure illustrated by Figures 22 and 23, that has already been described, can be applied to determine the influence of dual wheels on highway vehicles on flexible pavement thickness requirements.

Figure 41 provides a rearrangement of the design information contained in Figure 19. The ordinate is load in pounds on an isolated single wheel (equivalent single wheel load), the abscissa is thickness of flexible pavement in inches, and each main curve represents a given value of subgrade strength as measured by a 12-inch diameter bearing plate at 0.2 inch deflection for 10 repetitions of load.

Figure 41 is similar to Figure 23, but illustrates the decrease in flexible pavement thickness requirements for highways that can be made by equipping trucks and buses with dual wheels. The dual wheel arrangement shown in Figure 41, for which d = 4 inches and S = 13.5 inches, represents centre to centre spacing of duals on a heavy duty truck. Because of the relatively close spacing of dual wheels on trucks and buses, duals are much less effective for reducing flexible pavement thicknesses on highways, than is the case with the much more widely spaced duals on the landing gear of aircraft operating on runways. When the dual wheel illustrated in Figure 41 carries a load of 9,000 pounds, the curve st indicates the thickness of flexible pavement needed to carry it for different values of subgrade support. When compared with the thickness requirements for 9,000 pounds on a single wheel, the curve st

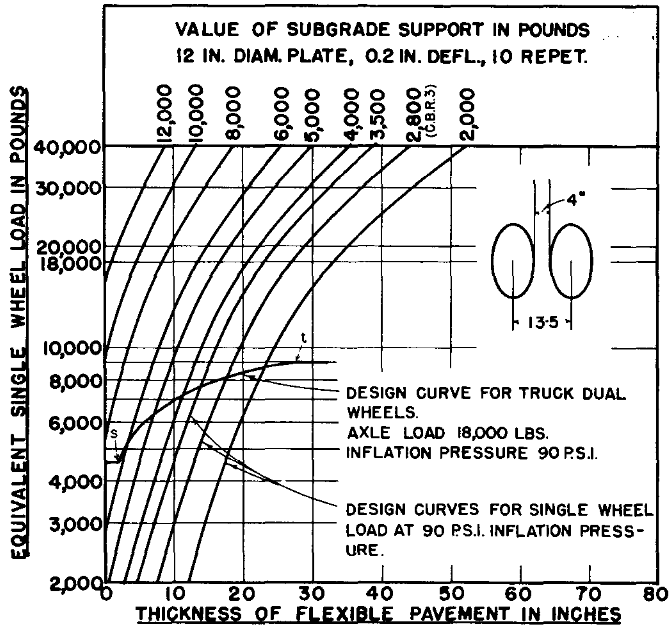

Fig. 41. Flexible Pavement Design and Evaluation Chart for Single and Dual Wheels on Trucks (Tire Inflation Pressure 90 P.S.I.).

indicates that for a load of 9,000 pounds on this dual wheel arrangement, the required thickness is decreased by from about 5 per cent on very weak subgrades, to about 25 per cent on strong subgrades. For duals with closer centre to centre spacings, the reductions in flexible pavement thickness would be even smaller than these.

Many highway departments have established a maximum legal axle load limit of 18,000 pounds. When this axle weight is equally distributed, a load of 9,000 pounds is imposed on the wheels at each extremity of the axle. The curve st in Figure 41 demonstrates that for a very weak subgrade, capable of supporting only 2,800 pounds on a 12-inch diameter bearing plate at 0.2 inch deflection for 10 repetitions of load, (C.B.R. = 3), if 9,000 pounds is carried on dual wheels spaced 13.5 inches centre to centre, the equivalent single wheel load is 8,100 pounds. Consequently, in this case, a flexible pavement capable of supporting a load of 8,100 pounds on a single wheel would support a load of 9,000 pounds on dual wheels.

Influence of Eccentricity of Axle Loadings

For purposes of design, it is normal practice to assume that the wheel load to be carried is one half the axle loading anticipated. While little actual data are available, it is likely that the axle weights of trucks are seldom symmetrical about the centre of the axle, even though symmetrical distribution of weight may be the objective when the vehicles are being loaded. Consequently, the load at one end of the axle tends to be less than one half, and that at the other end of the axle tends to be greater than one half the axle load. In addition, even if an axle has been loaded symmetrically when standing on a flat surface, the end of the axle nearer the outer edge of the pavement during travel tends to impose more than one half the axle weight because of the crown that a highway ordinarily provides from centre to the outside. Studies made during the W.A.S.H.O. Road Test at Malad, Idaho, (14), indicated that for an axle showing symmetrical loading on a flat surface, the load on the end of the axle in the outer wheel path was increased by several hundred pounds during travel, due to the crown of the road surface.

Larger trucks are usually equipped with dual tires. As noted in the preceding section, the substitution of duals for a single wheel tends to *reduce* thickness requirements. On the other hand, lack of symmetry in axle loadings, and crown in the road surface, places more than one half the axle load on the wheels at the one end of the axle. This additional load *increases* flexible pavement thickness requirements. Therefore, until more reliable data become available, whenever wheel loads are taken to be one half the axle loading, it is not unreasonable to assume that the normal relatively small decrease in thickness requirements that the substitution of dual for single wheels would ordinarily justify, is nullified by the unevenness of axle loading. Consequently, because of the eccentricity of axle loading, when wheel loads are assumed to be one half the axle weight, good design would seem to require the use of the flexible pavement thickness requirements for single wheel loads shown in Figure 19, even when trucks are equipped with duals.

On the other hand, for trucks for which *single wheels* are standard equipment, the design wheel load should be increased because of this lack of symmetry in axle loading. Under these conditions, it would not be unreasonable to assume an increase of 10 per cent over the nominal load on a *single wheel* (one-half of the axle weight) to allow for the unequal distribution of the axle load to the wheels at each end of the axle. In this case, if the axle weight to be carried by the flexible pavement is 18,000 pounds, the design load on a *single wheel* would be not 9,000 pounds, but 9,900 pounds.

Incidentally, because of failure to recognize this lack of symmetry in axle loading, and the tendency to assume that the axle weight is divided equally between the wheels at each end of the axle, flexible pavement thickness requirements expressed in terms of axle weights can be somewhat misleading, and could result in underdesign. It is for this reason, that for all diagrams pertaining to thickness design in this paper, flexible pavement thickness requirements are shown in terms of *wheel loads*.

Effect of Tandem Axle Spacings on Trucks

If a given flexible pavement will support 18,000 pounds on a single axle, the maximum legal weight permitted by most highway departments, how much load will it carry on two tandem axles spaced 48, 50, 60, etc., inches apart? This is one of the unsolved problems of flexible pavement thickness design.

The American Association of State Highway Officials recommends the use of a table in which the load on any group of axles is expressed in terms of the distance in feet between the extreme axles of the group (16). This relationship is widely used. For a flexible pavement that can just support 18,000 pounds on a single axle, A.A.S.H.O. recommends a corresponding load of 32,000 on tandem axles if they are spaced 4, 5, 6, or 7 feet apart.

Trucks equipped with both single and tandem axles were used to provide traffic for testing the W.A.S.H.O. test road (17). Consequently, analysis of the data from this traffic testing enabled a relationship between single and tandem axle loadings to be established. On the basis of the areas of the test road that had developed distress under traffic, it was found that on the sections with a 2-inch thickness of bituminous surfacing, a tandem axle load of 28,300 pounds corresponded to 18,000 pounds on a single axle, while 36,400 pounds on tandem axles was equivalent to a single axle load of 22,400 pounds. For the test sections paved with 4 inches of bituminous concrete, tandem axle loads of 28,000 and 33,600 pounds were equivalent to single axle loads of 18,000 pounds and 22,400 pounds respectively (14). For the trucks employed for the W.A.S.H.O. road test, dual wheels were used, and the spacing between the tandem axles ranged from 48 to 51 inches (17).

The W.A.S.H.O. test road results indicate that a load of slightly more than 28,000 pounds on tandem axles spaced 48 to 51 inches apart, is equivalent to 18,000 pounds on a single axle. This is a more conservative relationship than that recommended by the A.A.S.H.O. table previously referred to (16), in which a load of 32,000 pounds on tandem axles is considered to correspond to a single axle load of 18,000 pounds.

It would be of considerable assistance to flexible pavement thickness design for highways, if a method were available to establish tandem axle loadings equivalent to any given single axle load. It will be shown in Figures 42 to 45, that the procedure already illustrated by Figures 22 and 23 appears to have considerable merit for this purpose.

It will be recalled that the method illustrated by Figures 22 and 23 was used to determine the thickness of flexible pavement required to carry any given aircraft loading either on dual wheels, or on a dual tandem landing wheel assembly. This same method can be employed to determine the total weight on the tandem axles of a highway vehicle that corresponds to a given load on a single axle, e.g., 18,000 pounds.

Figure 42 is similar to Figure 41, but contains one design curve for 18,000 pounds on a single axle (9,000 pounds on dual wheels), lm, another design curve for 28,000 pounds on tandem axles (14,000 pounds on the two sets of dual wheels on one side of the tandem axles), no, and a

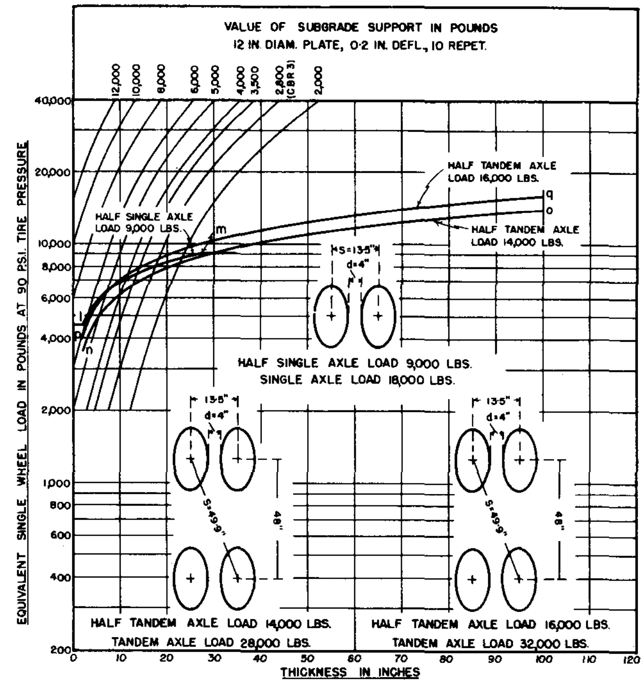

Fig. 42. Determination of Tandem Axle Loads Corresponsing to a Single Axle Load of 18,000 Pounds (Semi-Log. Diagram; 90 P.S.I. Tire Inflation Pressure).

third design curve for 32,000 pounds on tandem axles (16,000 pounds on the two sets of dual wheels on one side of the tandem axles), pq. In all cases, the centre to centre spacing between duals is 13.5 inches, and the spacing between tandem axles is 48 inches.

It is clear from Figure 42, that at a flexible pavement thickness requirement of about 8 inches, the curve pq representing equivalent single wheel loads corresponding to 16,000 pounds on dual tandem wheels (32,000 pounds on tandem axles), crosses the curve lm representing equivalent single wheel loads corresponding to 9,000 pounds on dual wheels (18,000 pounds on a single axle). This means that for pavement thicknesses up to about 8 inches, a flexible pavement that will support a load of 9,000 pounds on dual wheels (18,000 pounds on a single axle), will also support 16,000 pounds on dual tandem wheels (32,000 pounds on tandem axles). However, for flexible pavement thicknesses greater than about 8 inches, a tandem axle weight of 32,000 pounds will overload a flexible pavement that is designed to just support 18,000 pounds on a single axle (9,000 pounds on duals).

Curve no, representing equivalent single wheel loads corresponding to 14,000 pounds on dual tandem wheels (28,000 pounds on tandem axles), crosses the extension of the curve lm at a flexible pavement thickness requirement of about 28 inches. Consequently, for pavement thicknesses up to about 28 inches, a flexible pavement that will carry a load of 9,000 pounds on dual wheels (18,000 pounds on a single axle), will also support 14,000 pounds on dual tandem wheels (28,000 pounds on tandem axles). For pavement thicknesses greater than about 28 inches, a flexible pavement that is designed to just support 18,000 pounds on a single axle would be underdesigned for 28,000 pounds on tandem axles.

On the basis of the approach illustrated by Figure 42, it is apparent that for the average range of flexible pavement thicknesses required for heavy duty traffic, a tandem axle load of 28,000 pounds or slightly more, corresponds to a single axle load of 18,000 pounds. This is in very close agreement with the findings of the report on the W.A.S.H.O. Road Test, Part 2 (14), referred to earlier in this section. Both the design procedure described here, Figure 42, and the W.A.S.H.O. test road results, indicate that A.A.S.H.O.'s recommendation that 32,000 pounds on tandem axles should be considered equivalent to 18,000 pounds on a single axle (16), provides too generous a rating for the tandem axle load.

It should be particularly noted, that the design procedure illustrated by Figure 42 suggests that the relationship between corresponding tandem axle and single axle loads varies with the degree of subgrade support and with the thickness of flexible pavement. This relationship does not appear to be a constant as the A.A.S.H.O. recommendation implies, for example, 32,000 pounds on a tandem axle always corresponds to 18,000 pounds on a single axle (16). Figure 42 indicates that for a single axle load of 18,000 pounds, the corresponding tandem axle loading varies from slightly more than 32,000 pounds for flexible pavement thicknesses less than about 8 inches, to somewhat less than 28,000 pounds for flexible pavement thicknesses greater than about 28 inches.

Figure 43 has been included to show that lm, no, and pq, which are curved lines in the semi-log chart of Figure 42, are straight lines on the log-log diagram of Figure 43. As explained earlier, a log-log diagram like Figure 43, on which lm, no, and pq, are drawn as straight lines, forms the basis for establishing the locations of lm, no, and pq, as curved lines on Figure 42. The semi-log diagram of Figure 42 is preferred for the ultimate presentation of data, because flexible pavement thickness requirements can be read more easily from the arithmetic scale of its abscissa, than from the logarithmic scale of the abscissa of Figure 43, particularly when interpolation is required.

Figure 44 is similar to Figure 42, but the single axle load is 22,400 pounds instead of 18,000 pounds. One lane of the W.A.S.H.O. test road was subjected to traffic testing by a single axle load of 22,400 pounds.

Figure 44 indicates that for a single axle load of 22,400 pounds, the equivalent tandem axle loading varies from slightly more than 40,000 pounds for thicknesses of flexible pavement thickness smaller than about 7-1/2 inches, to less than 36,000 pounds for flexible pavement thicknesses greater than about 27 inches, and to less than 34,000 pounds for thicknesses of flexible pavement greater than about 32 inches. For the average range of flexible pavement thicknesses for heavy duty

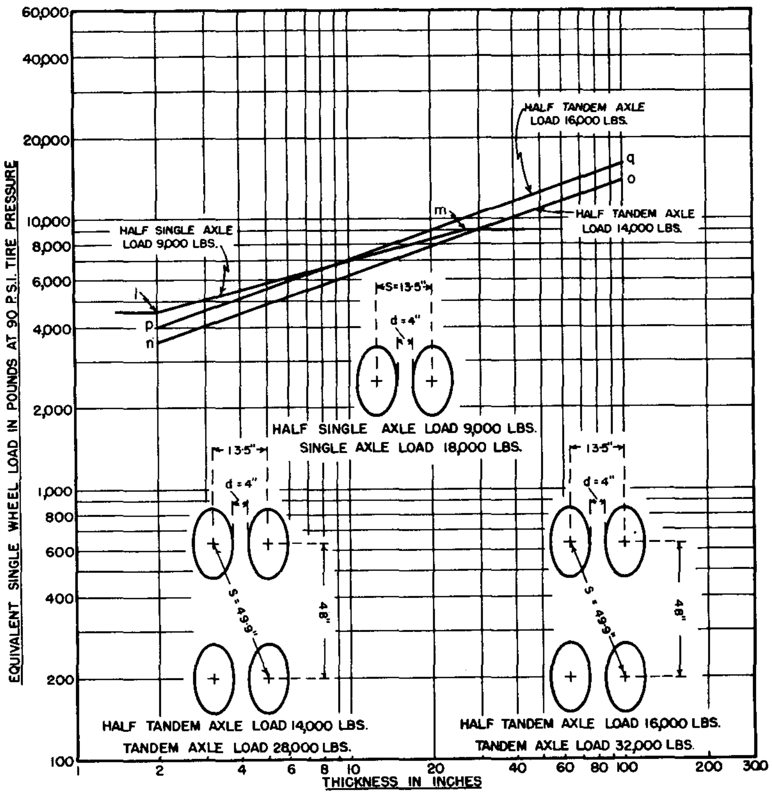

Fig. 43. Determination of Tandem Axle Loads Corresponding to a Single Axle Load of 18,000 Pounds (Log.-Log. Diagram; 90 P.S.I. Tire Inflation Pressure).

traffic, Figure 44 indicates that a tandem axle load of about 36,000 pounds would correspond to a single axle load of 22,400 pounds. Consequently, the design procedure illustrated by Figures 42 and 44 is again in good agreement with the results from the W.A.S.H.O. test road wherein tandem axle loads ranging from 33,600 to 36,400 pounds were reported to be equivalent to a single axle load of 22,400 pounds.

In Figure 45, the design procedure illustrated by Figures 42, 43, and 44, is employed to investigate the influence of the spacing of tandem axles on the tandem axle loading equivalent to a single axle load of 18,000 pounds. The tandem axle load is maintained constant at 32,000 pounds, but the tandem axle spacing is varied from 48 to 96 inches. Figure 45 indicates that the tandem axle load of 32,000 pounds is equivalent to a single axle load of 18,000 pounds at the following corresponding tandem axle spacings and thicknesses of flexible pavement,

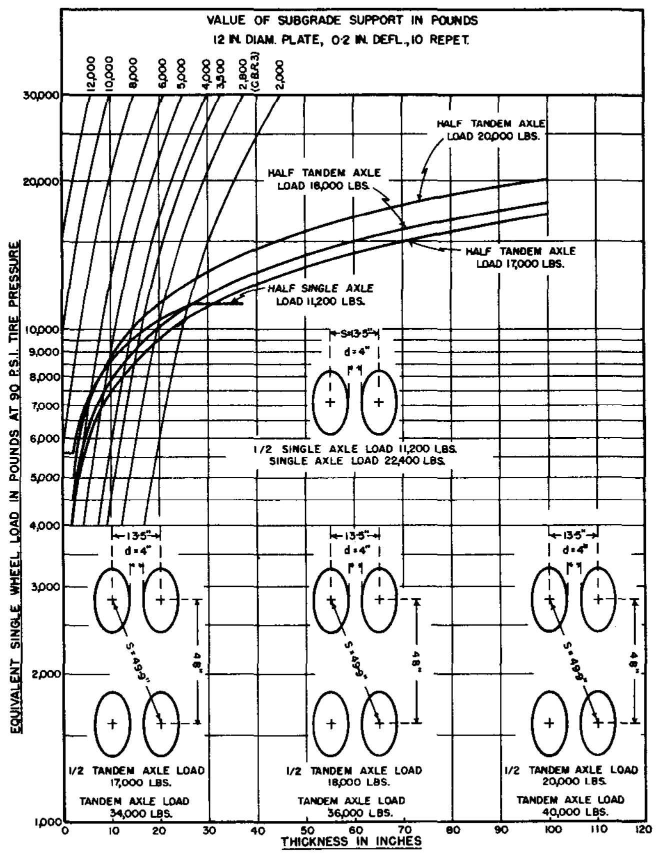

Fig. 44. Determination of Tandem Axle Loads Corresponding to a Single Axle Load of 22,400 Pounds (90 P.S.I. Tire Inflation Pressure).

Tandem axle spacing	For each tandem axle spacing shown, 32,000 pounds on tandem axles is equivalent to 18,000 pounds on a single axle when the flexible pavement thickness is not more than
48 inches	8 inches
60 "	11 "
72 "	15 "
84 "	27 "
96 "	30 "

Consequently, according to the design procedure illustrated by Figures 42, 43, 44, and 45, Figure 45 indicates that for the average range of flexible pavement thickness for heavy duty traffic, if a tandem axle load of 32,000 pounds is to be equivalent to a single axle load of 18,000

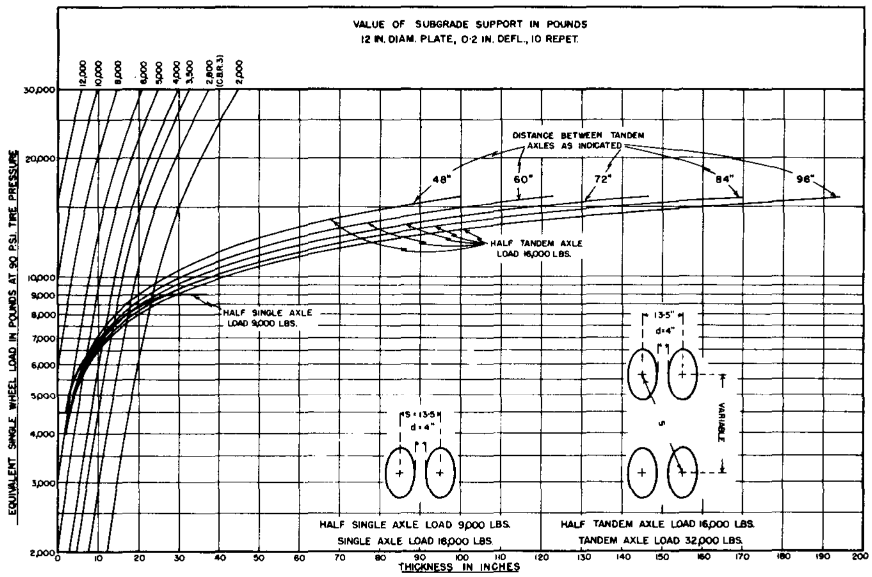

Fig. 45. Illustrating Influence of Flexible Pavement Thickness on Tandem Axle Spacing at Which 32,000 Pounds on Tandem Axles Is Equivalent to 18,000 Pounds on a Single Axle (90 P.S.I. Tire Inflation Pressure).

pounds, the minimum axle spacing must range from 72 to 96 inches (6 to 8 feet).

On the basis of Figures 42, 43, 44, and 45, the relationship between a tandem axle load and its equivalent single axle load is not a constant. For any given single axle load, the corresponding tandem axle load varies with the subgrade strength, thickness of flexible pavement, and the spacing between the tandem axles. Failure to recognize this varying relationship between tandem axle weights and corresponding single axle loads, could lead to overloading of flexible pavements designed on the basis of single axle weights but subjected to tandem axle loadings.

Influence of Traffic Volumes

Figure 46 presents the results of test data from traffic tests on full scale test sections reported by the Corps of Engineers (19), which demonstrate that flexible pavement thickness requirements depend very materially on the amount of traffic of a given wheel load to be carried. Figure 46 shows that the thickness required for capacity or unlimited traffic can be reduced by as much as 50 per cent or more, if the anticipated traffic volume is small. If the best line drawn through the data of Figure 46 is extended toward the left to one coverage, the thickness requirement becomes about 20 per cent of that specified for capacity

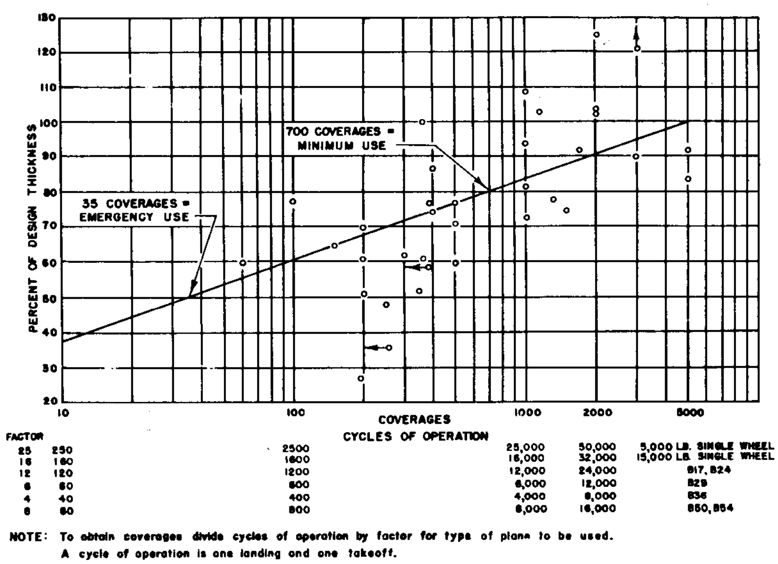

Fig. 46. Per Cent of Design Thickness Required for Various Airplane Coverages of Runways With Flexible Pavements.

traffic. (One coverage refers to one actual passage of a tire over a given point on a pavement.) This means that if a flexible pavement 40 inches thick is required to carry capacity traffic of a specified aeroplane wheel load on a runway over a given subgrade, a flexible pavement 8 inches thick on the same subgrade would support just one coverage of the given wheel load without failure.

Figure 46 is a semi-log graph of required pavement thickness versus number of traffic coverages. Because of the scattering of data in Figure 46, it may be questioned that the straight line shown is justified. However, Figure 46 bears a striking resemblance to Figure 47, which is a semi-log chart of pavement deflection versus number of repetitions of a given plate bearing test load at one test location, determined during the Department of Transport's investigation of runways at Canadian airports (8). Many similar graphs were obtained at other test locations during this investigation. Furthermore, Hveem has stated that test data obtained in California indicate that the thickness of flexible pavement required to support traffic increases directly with the logarithm of traffic coverages (18). Consequently, there is considerable evidence to justify the straight line relationship between thickness requirements and traffic coverages illustrated in Figure 46.

Figure 46 pertains to airport runway design. In Figure 48, the same principle has been applied to establish a relationship between traffic volume and flexible pavement thickness requirements for highways. Figure 48 was constructed on the basis of the following three assumptions:

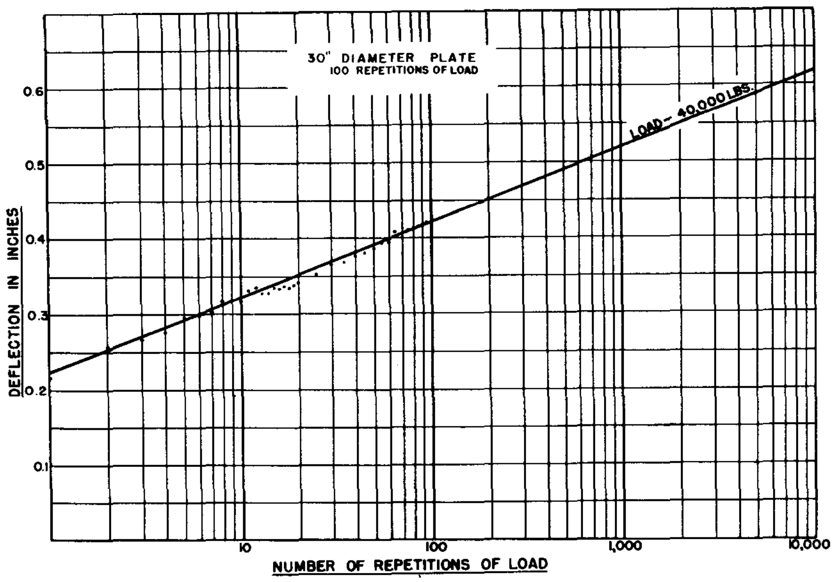

Fig. 47. Increase in Deflection Resulting from Repetitions of a Given Load.

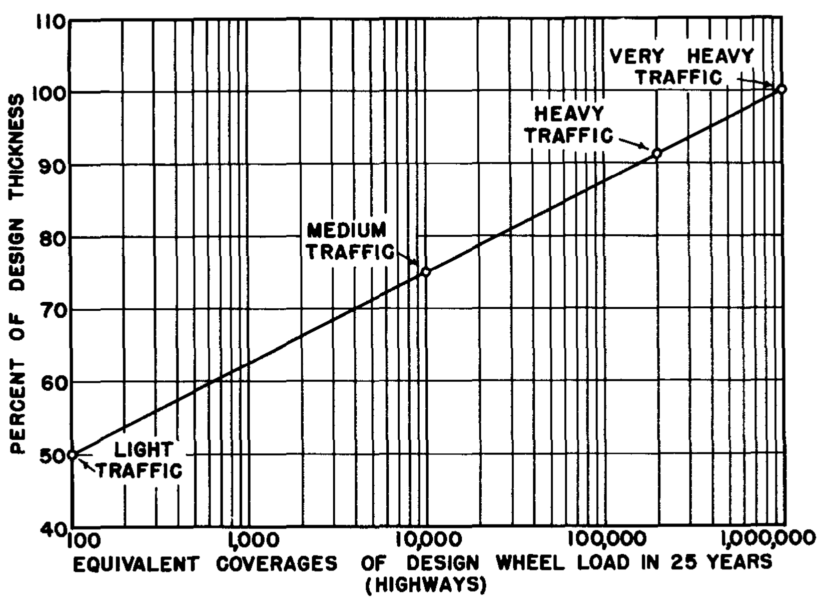

Fig. 48. Per Cent of Design Thickness Required for Various Intensities of Highway Traffic.

1. If a highway is to support capacity traffic volume, it must be designed to carry one million coverages of the design wheel load or its equivalent during a period of 25 years. This is represented by 100 per cent of design thickness in Figure 48.
2. It is assumed that 25 per cent of this design thickness will just support one coverage of the design wheel load or its equivalent without failure. This is slightly more conservative than Corps of Engineers' data indicate to be necessary, since as previously mentioned, extrapolation of the graph of Figure 46 to the left indicates that one coverage of the design wheel load could just be carried without failure by 20 per cent of the design thickness.
3. The per cent of design thickness required for any number of coverages of the design wheel load between one and one million can be obtained by joining with a straight line on a semi-log graph the points representing 25 per cent of the design wheel load for one coverage, and 100 per cent of the design wheel load for one million coverages, Figure 48.

Figure 48 indicates the reductions in flexible pavement thickness requirements that can be made for smaller traffic volumes. If 100 per cent of design thickness represents the thickness requirement for very heavy or capacity traffic, (one million coverages of the design wheel load or equivalent in 25 years), about 91 per cent of design thickness will be adequate for heavy traffic (100,000 coverages of the design wheel load or equivalent in 25 years), about 75 per cent of design thickness would be selected for medium traffic (10,000 coverages of the design wheel load or equivalent in 25 years), while 50 per cent of the design thickness would support light traffic (100 coverages of the design wheel load or equivalent in 25 years).

It will be realized that the light, medium, heavy, and very heavy categories of traffic indicated in Figure 48 are purely arbitrary classifications, and that they all refer to the same design wheel load or equivalent. Nevertheless, these arbitrary categories make it possible to recognize the wide range in flexible pavement thickness requirements for the light traffic of little travelled outlying rural roads, the medium traffic of more heavily travelled secondary highways and more lightly travelled primary highways, the heavy traffic of busy primary highways, and the very heavy traffic of highways that are operating at or very close to their maximum capacity.

On most highways, traffic consists of a large number of passenger cars with low wheel loads, a much smaller number of very large trucks with heavy wheel loads, and a considerable number of other vehicles that exert a whole spectrum of wheel loads between these two extremes. Before Figure 48 can be utilized for establishing the thickness needed for any given traffic volume, the influence on flexible pavement thickness requirements of the number and weight of each wheel load in the anticipated traffic stream must be determined. This means, for example, that the number of coverages of a 4,000-lb. wheel load that are equivalent to one coverage of a 9,000-lb. wheel load, insofar as flexible pavement thickness requirements are concerned, must be established, etc.

The ratios required for this purpose can be obtained from Figure 49, when the subgrade support is 2,500 pounds for a 12-inch diameter

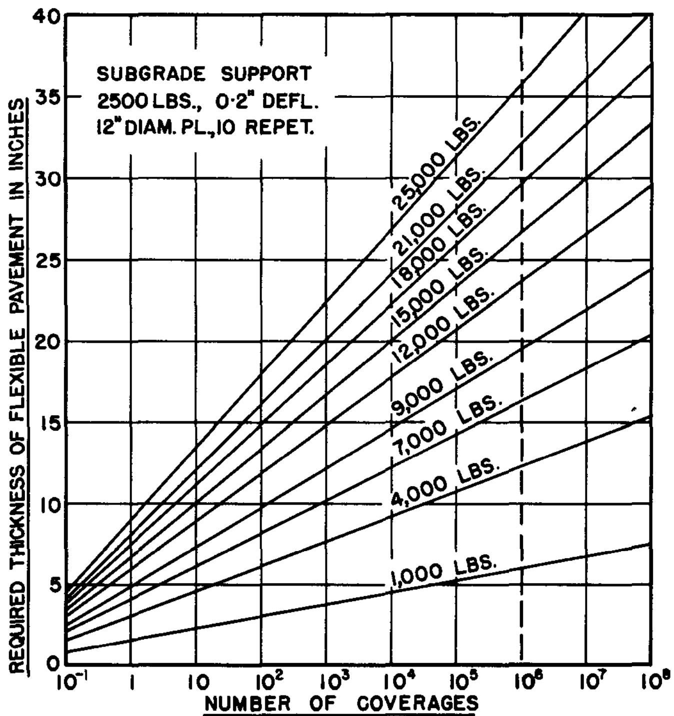

Fig. 49. Influence of Number of Traffic Coverages on Required Thickness of Flexible Pavement.

bearing plate at 0.2 inch deflection for 10 repetitions of load. This is a weak subgrade for which the corresponding in-place C.B.R. value is about 2.3. The thicknesses indicated for this subgrade support were read from Figure 19 for each wheel load, and were marked on the ordinate labelled 10^6 coverages (one million coverages) in Figure 49. Next, points representing 25 per cent of each of these thicknesses were marked off on the ordinate representing one coverage. The corresponding points for each wheel load were then joined by a straight line. For example, in the case of the 12,000-lb. wheel load, Figure 19 indicates a thickness requirement of 23.6 inches (for capacity traffic) for a subgrade support of 2,500 pounds (12-inch plate, 0.2 inch deflection, 10 repetitions of load). This thickness value is marked on the ordinate representing one million coverages (capacity traffic) in Figure 49. Twenty-five per cent of this thickness, or 5.9 inches, is marked on the ordinate representing one coverage. The straight line drawn through these two points indicates the thickness needed to carry any given number of coverages of a 12,000-lb. wheel load, for the subgrade support in question. Charts similar to Figure 49 can be prepared for other values of subgrade support.

From Figure 49 it can be seen that a given thickness of flexible pavement on a specified subgrade will just support a certain definite number of coverages of a given wheel load, but will carry various numbers of coverages of other wheel loads. For example, when the subgrade strength is 2,500 pounds on a 12-inch diameter plate at 0.2 inch deflection for 10 repetitions of load, Figure 49 shows that a thickness of 15 inches will just support the following numbers of coverages of the several wheel loads listed.

Table I

Wheel Load in Lbs.	Number of Coverages That Can Be Just Supported
25,000	22
21,000	53
18,000	107
15,000	309
12,000	1,175
9,000	10,352
7,000	108,400
4,000	54,954,000

Similar data for each of a wide number of thicknesses have been taken from Figure 49 and plotted in a different form in Figure 50. From Figure 50, the number of coverages of various wheel loads that a flexible pavement of a specified thickness can support can be read off and compared.

Figures 51 and 52 are similar to Figure 50, but Figure 50 applies only to a subgrade support of 2,500 lbs., while Figures 51 and 52 pertain to subgrade supports of 4,000 lbs. and 7,000 lbs., respectively, all on a 12-inch diameter bearing plate at 0.2 inch deflection for 10 repetitions of load.

Figures 50, 51, and 52, indicate that the relationships between the number of coverages of different wheel loads that can be just supported by a flexible pavement *is not constant*, but depends upon the supporting value of the subgrade and the thickness of the flexible pavement.

The problem of how frequently wheel loads of different magnitudes occur in average highway traffic must now be considered. For some years, the U. S. Bureau of Public Roads has published an annual review (20) concerning traffic trends on main rural roads in the United States. This report provides information on a number of important items, (a) the numbers of vehicles of different types, passenger cars, trucks, buses, etc., per 1,000 vehicles of average traffic on main rural roads in the U. S. A., (b) the average empty and loaded gross weights of truck

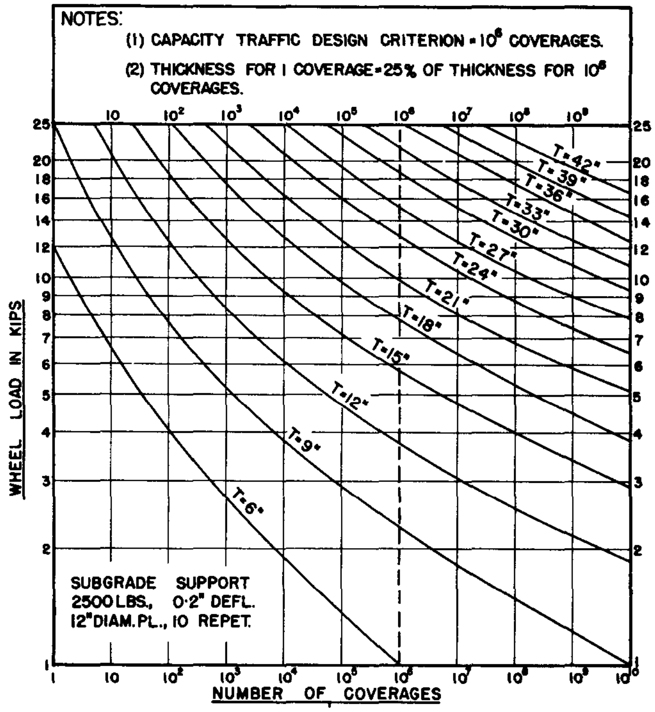

Fig. 50. Relationships Between Wheel Loads, Flexible Pavement Thicknesses and Number of Coverages.

and truck combinations of various kinds, (c) the percentages of loaded and empty truck and truck combinations of different types, and (d) the frequency and amount of overloading of the various trucks and truck combinations. The Bureau of Public Roads' annual review of traffic trends does not indicate how the gross weights of either empty or loaded vehicles are divided between the various axles. Consequently, some assumptions must be made concerning the distribution of vehicle weights to the different axles. When this is done on what seems to be a reasonable basis, the number and weights of axle loadings shown in Table I are obtained for 1,000 vehicles of average traffic on main rural roads in the United States.

By assuming that one half the axle load shown in Table I is carried by the wheels at each end of the axle, the number of wheel loads of different weights per 1,000 vehicles of average traffic on main rural roads in the United States can be determined. These are listed in Table III.

One more factor must be evaluated. What minimum number of trips of each wheel load of different magnitude is required for one coverage of the pavement at the point where the pavement receives most traffic? During average travel, the distance of the wheels from the outer edge

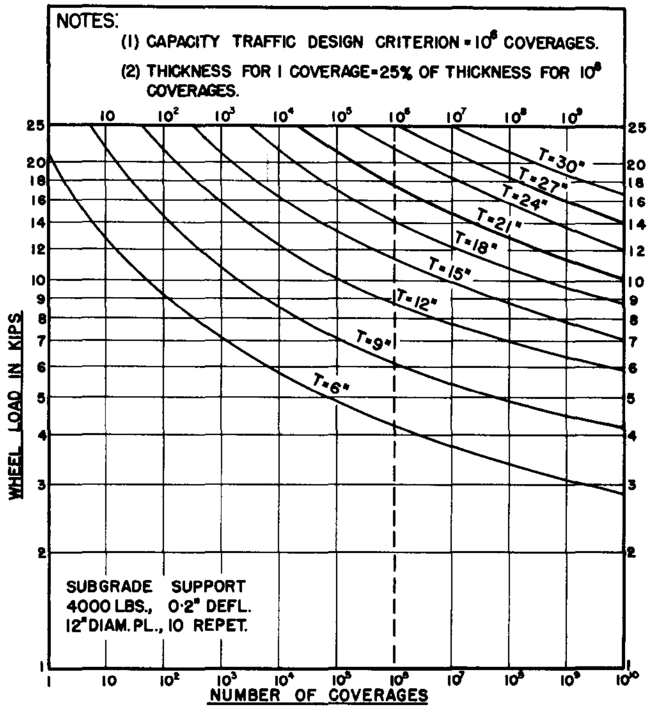

Fig. 51. Relationships Between Wheel Loads, Flexible Pavement Thicknesses and Number of Coverages.

Table II. Number of Single Axles or Equivalent Single Axles Carrying the Weight Shown per 1,000 Vehicles of Average Traffic on Main Rural Highways in the United States

Axle Loading on Single Axle or Equivalent Lbs.	Number of Single Axle Loadings or Equivalent Single Axles of Each Weight per 1,000 Vehicles of Average Traffic on Main Rural Roads in the U.S.A.
26,000	0.9
24,000	1.3
22,000	4.1
20,000	4.3
18,000	18.7
16,000	30.1
14,000	28.7
12,000	23.6
10,000	41.1
8,000	62.4
6,000	57.9
4,000	44.7
3,000	67.3
2,000	1,685.8
	2,070.9

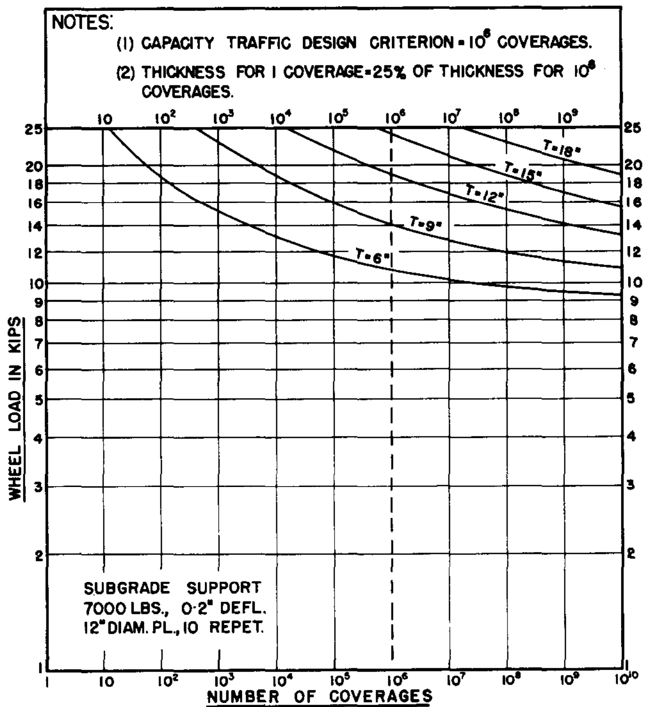

Fig. 52. Relationships Between Wheel Loads, Flexible Pavement Thicknesses and Number of Coverages.

Table III. Number of Wheel Loads of the Weights Shown per 1,000 Vehicles of Average Traffic on Main Rural Roads in the United States

Wheel Loading Lbs.	Number of Wheel Loads of Each Weight per 1,000 Vehicles of Average Traffic on Main Rural Roads in the United States
13,000	0.9
12,000	1.3
11,000	4.1
10,000	4.3
9,000	18.7
8,000	30.1
7,000	28.7
6,000	23.6
5,000	41.1
4,000	62.4
3,000	57.9
2,000	44.7
1,500	67.3
1,000	1,685.8
	2,070.9

or centre of the pavement varies considerably from vehicle to vehicle. Consequently, more than one trip of any given wheel is required for one coverage of the point on the wheel path receiving most traffic. It should be obvious that the pavement at some critical distance from its outer edge or centre receives the greatest number of coverages per 1,000 vehicles of average traffic. It is the number of coverages of different wheel loads at this critical point (or line) that is required for flexible pavement thickness design. The Bureau of Public Roads has made a special study of the variation in the lateral position of passenger cars and trucks travelling on a highway relative to the centre of the pavement (14, 21, 22). On the basis of widths of single tires and duals, and the Bureau's findings concerning variations in the positions of travelling vehicles relative to the centre line of the pavement, an attempt has been made to determine the number of trips of each wheel load required for one coverage of the point or line on the pavement receiving maximum coverage, and the results are listed in Table IV.

Table IV. Average Number of Trips of Each Wheel Load Required For One Coverage of the Point or Line on the Pavement Receiving Maximum Coverage of the Wheel Load

Wheel Load Lbs.	Number of Trips Required for One Coverage
14,000	1.35
13,000	1.38
12,000	1.42
11,000	1.46
10,000	1.50
9,000	1.55
8,000	1.61
7,000	1.69
6,000	1.80
5,000	2.2
4,000	2.6
3,000	3.5
2,000	4.2
1,500	4.4
1,000	4.2

For an earlier paper (23), when calculating the number of trips of vehicles with dual tires required for one coverage, the width of the loaded area employed was from outside of tread to outside of tread on the duals. This of course is the most conservative approach. However, it might be argued that it is too conservative, and would penalize large vehicles with dual wheels too severely, because very little more than one trip is required for one coverage of the point (line) on the pavement receiving the greatest number of coverages. For the present paper therefore, the effective width of the loaded area under dual tires is taken as the diameter of an equivalent circle obtained by dividing the total wheel load by the tire inflation pressure. This increases somewhat the number of trips of a dual wheel required for one coverage. The number of trips required for one coverage of each large number of wheel loads, determined on this basis, has been listed in Table IV.

The heavier wheel loads tabulated in Table III are ordinarily carried on dual tires. It was shown earlier in this paper that a given load on dual tires is ordinarily equivalent to a somewhat smaller load on a single tire, insofar as flexible pavement thickness requirements are concerned, although the difference is not large for the thicknesses of flexible pavement needed for heavy loads over poor subgrade soils. However, it was also pointed out that probable eccentricity of axle loading tends to nullify this normal difference between dual wheel and equivalent single wheel loads. Consequently, for the balance of this section, it is assumed that although the heavier wheel loads are normally carried on dual tires, the flexible pavement thickness requirements are given by Figure 19, which is based on single wheel loads.

The procedure for determining the influence of any measured or estimated traffic count on the flexible pavement thickness requirement for a proposed or existing highway project, can now be illustrated. Suppose, for example, the following design information is available:

Subgrade support - 2,500 pounds on a 12-inch diameter plate, 0.2 inch deflection, 10 repetitions of load.
Wheel load distribution - represented by average traffic on main rural roads of the United States.
Traffic volume - unlimited traffic, 20,000 vehicles per lane per day.
Problem - To determine the thickness of flexible pavement required to carry unlimited traffic for 25 years on this project.

A trial and error solution is required. For the first trial, it will be assumed that the flexible pavement thickness requirement is that for a single wheel load of 12,000 pounds for unlimited traffic (one million coverages in 25 years). The solution to this problem is worked out below:

Table V

Wheel Load Lbs.	Number of Trips of Each Indicated Wheel Load per 1,000 Vehicles	Conversion Factor No. 1 Converting Wheel Trips to Coverages	Number of Coverages of Each Wheel Load	Conversion Factor No. 2 Converting to Number of Coverages of Equivalent Wheel Load of 12,000 lbs.	Number of Coverages Equivalent to Wheel Load of 12,000 lbs.
13,000	0.9	1.38	0.65	0.68	0.96
12,000	1.3	1.42	0.92	1.0	0.92
11,000	4.1	1.46	2.81	2.83	0.99
10,000	4.3	1.50	2.87	8.92	0.32
9,000	18.7	1.55	12.06	44.9	0.27
8,000	30.1	1.61	18.70	225.0	0.08
7,000	28.7	1.69	16.98	1,590.0	0.01
6,000	23.6	1.80	13.11	15,900.0	---
5,000	41.1	2.2	18.82	---	---
4,000	62.4				
3,000	57.9				
2,000	44.7				
1,500	67.3				
1,000	1,685.8				
					3.55

Number of equivalent 12,000-lb. wheel load coverages
per 1,000 vehicles = 3.55 per 1 year (71.0)(365) = 25,900
per 1 day (20,000 vehicles per lane) = (3.55)(20) = 71.0 per 25 years (25,900)(25) = 647,500

For this first trial, a flexible pavement thickness of 23.7 inches was selected (Figure 19), which is capable of supporting one million coverages of a 12,000-lb. wheel load or equivalent in 25 years. The above data indicate that this would provide some overdesign, since the anticipated traffic would actually provide only 647,500 coverages of this wheel load or equivalent in 25 years.

The method for determining Conversion Factor No. 2 in the first trial above should be explained. From Figure 19, for a subgrade support of 2,500 pounds on a 12-inch diameter plate at 0.2 inch deflection for 10 repetitions of load, a wheel load of 12,000 pounds requires a flexible pavement thickness of 23.7 inches. Turning to the curve labelled "T = 24 inches" in Figure 50, corresponding coverages for various wheel loads can be read off as indicated below:

Table VI

Wheel Load	Coverages Indicated by 24-inch Thickness Curve, Figure 50	Coverages in Terms of Unit Coverage for a Wheel Load of 12,000 lbs.
13,000	6.76×10^5	0.68
12,000	1.58×10^6	1.00
11,000	4.47×10^6	2.83
10,000	1.41×10^7	8.92
9,000	7.08×10^7	44.9
8,000	3.55×10^8	225.0
7,000	2.51×10^9	1,590.0
6,000	2.51×10^{10}	25,100.0

By dividing all figures in the middle column by 1.58×10^6, the corresponding values in the right hand column are obtained. The right hand column indicates the number of coverages of other wheel loads that are equivalent to one coverage of a 12,000-lb. wheel load, insofar as flexible pavement thickness requirements are concerned.

For the second trial, it will be assumed that the thickness of flexible pavement required is that for a single wheel load of 11,700 pounds for unlimited traffic (one million coverages in 25 years). From Figure 19, this thickness requirement is seen to be 23.3 inches. On this basis, the second trial and error solution to this problem is shown on the following page.

For the second trial, a flexible pavement thickness of 23.3 inches was selected, (Figure 19), which is capable of supporting one million coverages of a wheel load of 11,700 pounds or equivalent in 25 years, when the subgrade support is 2,500 pounds on a 12-inch diameter plate at 0.2 inch deflection for 10 repetitions of load. The data obtained for the second trial indicate that this thickness would result in very slight underdesign, since the anticipated capacity traffic volume would actually provide 1,003,250 coverages of a wheel load of 11,700 pounds or equivalent in 25 years. However, this solution is within 0.3 per cent of one million coverages, and this degree of underdesign is negligible from the point of view of practical flexible pavement design.

Table VII

Wheel Load Lbs.	Number of Trips of Each Indicated Wheel Load per 1,000 Vehicles	Conversion Factor No. 1 Converting Wheel Trips to Coverages	Number of Coverages of Each Wheel Load	Conversion Factor No. 2 Converting to Number of Coverages of Equivalent Wheel Load of 11,700 lbs.	Number of Coverages Equivalent to Wheel Load of 11,700 lbs.
13,000	0.9	1.38	0.65	0.32	2.03
12,000	1.3	1.42	0.92	0.75	1.23
11,700				1.00	
11,000	4.1	1.46	2.81	2.11	1.33
10,000	4.3	1.50	2.87	6.65	0.43
9,000	18.7	1.55	12.06	33.40	0.36
8,000	30.1	1.61	18.70	167.0	0.11
7,000	28.7	1.69	16.98	1,183.0	0.01
6,000	23.6	1.80	13.11	11,830.0	---
5,000	41.1	2.20	18.82	---	---
4,000	62.4				
3,000	57.9				
2,000	44.7				
1,500	67.3				
1,000	1,685.8				
					5.50

Number of equivalent 11,700-lb. wheel load coverages
per 1,000 vehicles = 5.50
per day (20,000 vehicles per lane) = (5.50)(20) = 110.0
per year = (110.0)(365) = 40,150
per 25 years = (40,150)(25) = 1,003,250

Consequently, the required solution for this particular problem is a flexible pavement thickness of 23.3 inches, which is associated with one million coverages of a wheel load of 11,700 pounds or equivalent in 25 years. This represents the flexible pavement thickness requirement for capacity traffic, (20,000 vehicles per lane per day for 25 years), having the wheel load distribution of average traffic on main rural roads in the United States in 1954, when the subgrade support is 2,500 pounds on a 12-inch diameter bearing plate at 0.2 inch deflection for 10 repetitions of load, (C.B.R. = 2 approximately).

The extreme sensitivity of this approach, and its ability to pinpoint the required thickness of flexible pavement within an extraordinarily narrow range, should be noted. This sensitivity is demonstrated by the fact that a thickness of 23.7 inches employed for the first trial provided noticeable overdesign, while 23.1 inches selected for the second trial resulted in very slight underdesign.

For an earlier paper on this topic (23), the full width of dual wheels from outside of tread to outside of tread was used when determining the traffic coverages of each wheel load per 1000 vehicles of average traffic on U.S.A. main rural roads in 1954. For the same problem that has just been considered in this paper, this resulted in a flexible pavement thickness requirement of 23.6 inches, associated with capacity traffic of a wheel load of 11,900 pounds or equivalent, as the solution. For the present paper, the traffic coverages for each dual wheel were determined on the basis of an equivalent wheel width equal to the diameter of a circle representing the quotient of the wheel load divided by the tire inflation pressure. However, it should be noted that the effect of this refinement is very small, since for the same problem, it resulted in a flexible pavement thickness requirement of 23.3 inches, associated with capacity traffic of a wheel load of 11,700 pounds or equivalent.

Incidentally, from Tables V and VII for the first and second trials for the solution to the above problem, it will have been observed that on the basis of the wheel load distribution per 1000 vehicles of average traffic on main rural roads in the United States in 1954, the relatively small number of very heavy wheel loads is responsible for the thickness of flexible pavement required. From both Tables V and VII, it is apparent that wheel loads smaller than about 8,000 pounds had almost no effect on the determination of the thickness of flexible pavement found to be necessary for capacity volume of average traffic. Consequently, according to the approach to the problem that has just been described, it is the very heavy wheel loads of 8,000 pounds and higher, which make up less than 3 per cent of the axles per 1000 vehicles, and less than 5 per cent of the total vehicle traffic, that are responsible for the flexible pavement thickness required for average traffic, as represented by average traffic on main rural highways in the United States in 1954.

For traffic volumes less than capacity, and for pavement life expectancies of less than 25 years, an approach similar to that just described can be employed.

It should be emphasized that the traffic composition employed in this section for illustrative purposes, was assumed to be that reported by the U. S. Bureau of Public Roads as the average for main rural highways in the United States as a whole for 1954. It should be particularly noted that the proportion of heavy trucks to light trucks, buses, and passenger cars could be quite different from this on individual projects, and would result in different thickness requirements than the examples given have indicated. In addition, assumptions have been made concerning weight distribution to various axles, Table II, which might be found to be somewhat different than shown, if detailed axle load data were available. However, it has been the main purpose of this section to illustrate the basic principles of a method that could be applied to determine the influence of traffic volume, axle weight distribution per 1,000 vehicles, wheel load coverages, etc., on flexible pavement thickness requirements. Further refinements of the method can be made as more data on each of the factors involved become available.

It is an outstanding advantage of this method, that it shows *the precise magnitude of the wheel load* on which the design of the flexible pavement must be based for the traffic to be carried.

Effect of Frost Action and Climate

In northern countries, the climatic factor that has the greatest effect on flexible pavement thickness requirements is frost action. Because of the detrimental effect of frost action on roads, it is common practice to impose special restrictions reducing axle loads to one-half or less of the legal limit for several weeks each year during the spring break-up period.

One method that has been proposed to overcome the detrimental effect of frost on roads and runways, is a blanket of granular material of sufficient thickness to insulate the subgrade from frost penetration. In most of Canada, and probably in the majority of the states just south of the International Boundary, frost penetrates to a depth of 5 to 6 feet or more each winter. Consequently, it is an economic impossibility to provide a blanket of granular material that will prevent freezing of the subgrade of even the primary roads of an entire highway system under these extreme cold weather conditions. Furthermore, it is worth recalling in this connection, that for the W.A.S.H.O. Road Test, it is reported that the average penetration of frost into the subgrade was about 11 inches during the first winter, and about 15 inches during the second, and that *the depth of frost penetration was the same regardless of the thickness of overlying flexible pavement, (base plus surface), ranging from 6 to 22 inches* (14). For this project at least therefor, there is little evidence of insulation from these thicknesses of base and surface.

The Motl Committee of the Highway Research Board has just completed a study of several years duration on the variation in the bearing capacity of flexible pavements month by month, and year by year (24, 25). While limited data were obtained by other methods, the Motl Committee generally employed the plate bearing test to determine the monthly and annual changes in flexible pavement bearing capacity at a large number of test locations on highways in the Northern United States.

Where frost penetration is deep, the Motl Committee found that during the spring break-up period the load supporting capacity of a flexible pavement would drop to as much as one half or less of its strength during late fall of the previous year, Figure 53. Furthermore, the strength of the flexible pavement did not return to a high value immediately following spring break-up, but increased more or less gradually month by month to reach a maximum in the late fall just before freezing, Figure 53. A limited number of plate bearing tests in Canada have verified this trend.

Where the surface and base course consist of material not affected by frost action, the entire loss in strength of a flexible pavement during the spring break-up period is due to loss of subgrade bearing capacity. That is, the strength loss of up to fifty per cent or more measured at the surface of a flexible pavement under these conditions is actually due to a loss of up to fifty per cent or more in the supporting value of the subgrade during spring break-up due to frost action.

For certain principle highways in some regions, load limit restrictions during the spring break-up period can not be tolerated. In addition, for important roads in many frost-affected areas there is a need

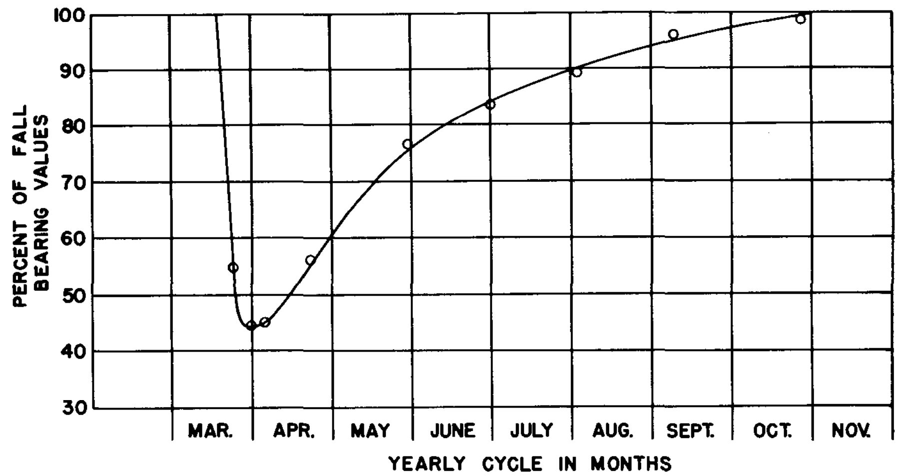

Fig. 53. Yearly Cycle of Loss and Recovery of Highway Supporting Values in Regions Subject to Deep Frost Penetration. (Motl Committee Report.)

and a trend to design flexible pavements of adequate strength to carry legal axle loadings and normal traffic throughout the entire year. How are flexible pavements to be designed to have the adequate thickness required to eliminate any need for load limit restrictions during the spring break-up period, and at the same time to avoid serious over-design? The method outlined below for this purpose has been employed for some time by the Department of Transport to design flexible pavements for runways at major Canadian airports. This method is based upon Figures 19, 48, 53, and 54.

The statement is frequently made that flexible pavement thicknesses should be designed on the basis of the worst subgrade condition that is likely to develop on each individual project. This is represented by the lowest point on the curve of Figure 53, which is the weakest condition of the subgrade during the spring break-up period. The writer is firmly opposed to this approach, since on this basis of lowest subgrade strength, the flexible pavement would be overdesigned for not only every part of the year except the week or so of minimum strength during the spring break-up, but, as will be shown presently, it would actually be over-designed for even this period of a week or two of least subgrade strength.

On the basis of Figure 48, it can be shown that some value of subgrade strength considerably above the minimum of the curve of Figure 53 should be selected for flexible pavement thickness design. This is justified because a highway carries only a portion of its lifetime traffic during the spring break-up period of about one month when the subgrade strength is at a low value. From Figure 54, taken from a Bureau of Public Roads' article (20), it is clear that the average traffic on main

Fig. 54. Average Daily Travel on All Rural Roads in the United States in 1954.

rural roads in the United States during the month of April is slightly less than one twelfth of the total annual traffic. The average traffic volumes during March and May are somewhat less and slightly more, respectively, than for April. Consequently, if a flexible pavement is designed to carry one million coverages of a given wheel load or its equivalent in 25 years, it will carry about one twelfth of this traffic, or about 80,000 coverages, during the spring break-up periods in 25 years, if these are of about one month's duration on the average. Figure 48 indicates that for 80,000 coverages, the required thickness of a flexible pavement is only about 86 per cent of the thickness needed for one million coverages.

For example, if the subgrade strength in the late fall is 6,000 pounds on a 12-inch diameter bearing plate for 0.2 inch deflection and 10 repetitions of load, and if one million coverages of a wheel load of 12,000 pounds or equivalent are to be carried in 25 years, Figure 19 indicates that a flexible pavement thickness of 9.7 inches is required. If for a month during the spring break-up period the subgrade strength drops to 50 per cent of the fall value, it becomes 3,000 pounds on a 12-inch plate at 0.2 inch deflection for 10 repetitions of load. For this much lower subgrade strength, according to Figure 19, one million coverages of a wheel load of 12,000 pounds or equivalent in 25 years would require a thickness of 20.7 inches. However, since only 80,000 coverages will be carried during spring break-up periods, each averaging one month, in 25 years, the required thickness is not 20.7 inches, but 86 per cent of 20.7 inches, or 17.8 inches. Therefore, a flexible pavement 17.8 inches thick will carry one million coverages of a 12,000-lb. wheel load or equivalent in 25 years over a subgrade that ranges in strength from 3,000 pounds (12-inch plate, 0.2 inch deflection, 10 repetitions of load) for about one month every spring, to 6,000 pounds (12-inch plate, 0.2 inch deflection, 10 repetitions of load) in the late fall.

Incidentally, it can be seen from Figure 19 that this required thickness of 17.8 inches for a wheel load of 12,000 lbs. or equivalent corresponds to an average subgrade strength of 3,600 pounds (12-inch plate, 0.2 inch deflection, 10 repetitions of load) throughout the year. Since 3,600 lbs. is 60 per cent of 6,000 lbs., the effective average yearly subgrade strength in this case is 60 per cent of the late fall subgrade bearing capacity.

Flexible pavement thickness design problems that involve a spring break-up period longer or shorter than one month, and losses in subgrade strength during this period that are greater or less than 50 per cent of the maximum value occurring in the late fall or at some other time of year, can be handled in a similar manner. This also applies to cyclical or other changes in subgrade strength due to climatic factors apart from frost.

It can be seen from Figure 48 that quite wide variations in the length of the spring break-up period have relatively little influence on the required thickness of flexible pavement. For example, Figure 48 shows that 50,000 coverages of the design wheel load or equivalent, that is, one twentieth of one million coverages, or an average spring break-up period of about 2.6 weeks, requires approximately 84 per cent of the thickness for one million coverages. On the other hand, 100,000 coverages, corresponding to a longer spring break-up period of approximately 5.2 weeks, requires about 87 per cent of the thickness for one million coverages.

Figure 53 emphasizes the need for carefully recording for future reference, the exact date when a subgrade bearing test is made, since any given subgrade can show a wide variation in strength, depending upon the time of year at which it is determined. This is particularly important if the strength of the subgrade is to be corrected to its value during the spring break-up period for flexible pavement design purposes.

If the strength of the subgrade in the late fall for a given year is assigned the rating of 100 per cent, it may be somewhat more or less than 100 per cent during the late fall in other years. In addition, the curve representing subgrade strength throughout the year should be evaluated for each locality, and for each soil type, since it may differ from that of Figure 53, particularly in regions where frost penetration is shallow (25).

By measuring the strength of the subgrade over a period of several years, a curve representing average values for the strength of the subgrade throughout the year can be established. It is important that these average values be determined, if either overdesign or underdesign of the thickness of flexible pavement is to be avoided.

If flexible pavements are being designed to carry capacity volume of normal traffic throughout spring break-up, it is the *average* value of subgrade strength during the spring break-ups throughout the 25-year period that is required, and *not* the lowest value of subgrade strength for some single spring break-up during this period, assuming that the lowest subgrade strength will not be more than about 20 to 25 per cent below the average value, which seems unlikely.

For highways designed to carry capacity traffic volume for 25 years, during any single spring break-up period of about one month's duration, only 1,000,000 ÷ (25)(12) = 3,333 coverages of the design wheel load or equivalent will be applied. Figure 48 shows that only about 69 per cent of the design thickness is needed for 3,333 coverages.

For the example given earlier in this section, the subgrade strength during spring break-up was assumed to drop to 3,000 pounds, (12-inch plate, 0.2 inch deflection, 10 repetitions), which was 50 per cent of its average fall value. Suppose that during one spring break-up in the 25-year period, the subgrade strength decreased to 40 per cent of the average fall value, becoming 2,400 pounds (12-inch plate, 0.2 inch deflection, 10 repetitions). Figure 19 shows that for this low subgrade strength value, 24.3 inches of flexible pavement would be required to support one million coverages of a wheel load of 12,000 pounds or equivalent in 25 years. However, as previously pointed out, for 3,333 coverages during a spring break-up period of one month's duration, only 69 per cent of this thickness, or (24.3)(0.69) = 16.8 inches is required.

It was shown in the earlier sample calculation in this section, that on the basis of an average subgrade strength of 3,000 pounds (12-inch plate, 0.2 inch deflection, 10 repetitions of load) for all spring break-ups during the 25-year period, a flexible pavement thickness of 17.8 inches would be required to carry normal capacity traffic. Since this exceeds the 16.8 inches of thickness indicated for a single spring break-up when the subgrade strength dropped to 20 per cent below average (from 3,000 to 2,400 pounds), it would appear that a flexible pavement thickness design procedure based upon average subgrade strength during the spring break-up periods over 25 years, and upon approximately 80,000 coverages of the design wheel load or equivalent, represents an adequate basis of design for capacity traffic for regions subject to frost penetration.

A similar approach can be employed to determine the thickness of flexible pavement required to carry categories of traffic less than capacity throughout spring break-up, without imposing the usual partial load limit restrictions during this period.

It should be emphasized that this approach to flexible pavement design is not intended to provide sufficient thickness over those small local areas of more or less accidental occurrence that are subject to frost heaving and frost boils. As pointed out previously in the section on subgrade design, good engineering requires that these small areas or pockets of soil that is susceptible to severe frost action, must be recognized and removed during construction of the subgrade, in accordance with standard practice followed so successfully by Ontario, Michigan, and other highway departments.

It is believed that this approach to the influence of climatic factors on flexible pavement thickness is thoroughly realistic, and that it also provides an economical solution. It recognizes that the subgrade of a road or runway undergoes a serious loss of strength during the spring break-up period. It makes full allowance for this serious decrease in subgrade strength for a period of a month or so each spring, and it indicates the thickness of flexible pavement that must be provided if normal traffic is to be carried throughout this period each year without damage to the pavement.

Effect of Braking Stresses

Based upon an ultimate strength approach to flexible pavement design, and assuming that the failure surfaces have the shape of logarithmic spirals when a flexible pavement is overloaded, it was pointed out in an earlier paper (26) that sections of a flexible pavement subjected to braking stresses, such as bus stops and traffic lights, require additional thickness. This is illustrated in Figure 55.

For the conditions illustrated in Figure 55(b) and (c), and in the absence of a safety factor, the required thickness of flexible pavement is 8.4 inches when there are no braking stresses. The additional thickness needed at bus stops and traffic lights because of braking stresses depends upon how vigorously the brakes are applied. If the brakes develop a coefficient of friction of 0.1 between tire and pavement, a total thickness of 10 inches is required. A coefficient of friction of 0.3 developed between tire and pavement as brakes are applied, increases the total flexible pavement thickness requirement to 14.2 inches.

Conversely, on the basis of Figure 55, if a uniform thickness of flexible pavement has been constructed throughout the entire length of a section of highway, and there are no signs of instability at bus stops and traffic lights, this is evidence that with the possible exception of these traffic stopping areas, the thickness has been overdesigned and is greater than necessary.

Influence of Quality of Base Course Material

Earlier in this paper, in a discussion of the base course constant K, it was pointed out that plate bearing tests conducted by the Canadian Department of Transport have indicated no dependable difference in the supporting values of various types of granular base course materials per unit thickness. It was suggested that this was probably due to the failure during construction, to compact the more stable highly angular aggregates to as high a relative density as that of the less angular and inherently less stable aggregates. Consequently, the higher relative densities of the more rounded aggregates tend to compensate for the greater angularity but lower relative densities of the highly crushed

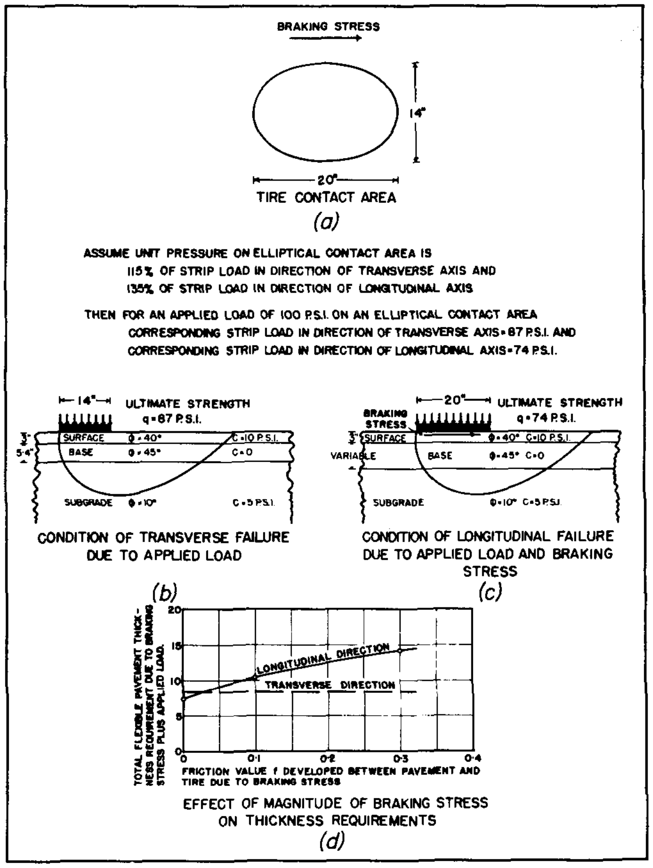

Fig. 55. Influence of Magnitude of Braking Stresses on Flexible Pavement Thickness Requirements.

materials, with the result that in actual practice both types develop approximately the same supporting value per unit thickness.

However, it is worth while to examine what effect highly stable versus less stable aggregates would have on base course thickness requirements, if they could be made to develop in the field the wide differences in stability that can be demonstrated for them in laboratory tests. This problem was considered in an earlier paper (26). For example, Figure 56(a) and (b) indicates the considerable reduction in the thickness of base course required to develop a specified ultimate strength of 112 p.s.i. for the flexible pavement as a whole, as the angle of internal friction of the cohesionless base course material is increased from 40° to 50°, which covers the range of quality from average pit-run gravel to crushed stone. Every factor in Figure 56(a) and (b) has been kept constant, except the thickness of the base, and the angle of internal friction of the base course material.

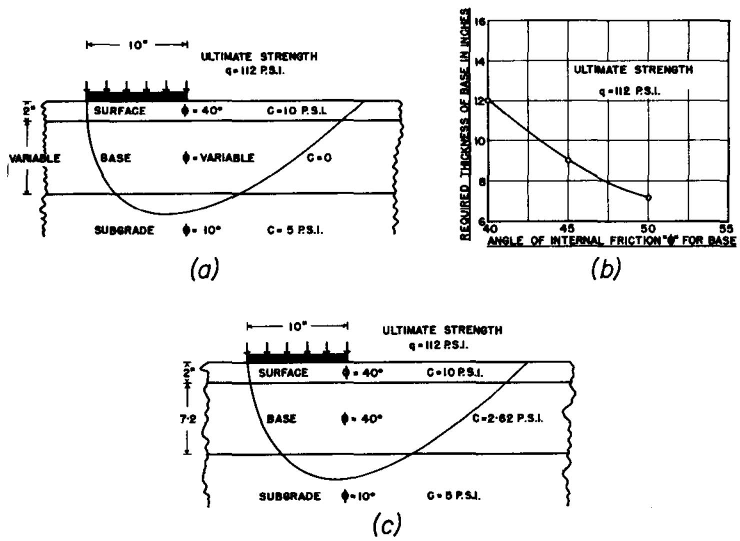

Fig. 56. Influence of Base Course Strength Characteristics on Base Course Thickness Requirements.

Figure 56(b) demonstrates that as the angle of internal friction of the base course material is increased from 40° to 50°, the required thickness of granular base course can be reduced from 12 to 7.2 inches while maintaining a constant ultimate strength of 112 p.s.i. for the flexible pavement structure. This represents a reduction of 40 per cent in the base course thickness requirement. Figure 56(b) is important because it illustrates the considerable decrease in base course thickness that would be possible by substituting highly stable aggregates for those of low inherent stability, if construction methods were capable of making highly crushed base course materials develop the remarkable stability characteristics in the field that they can be made to show in the laboratory.

In many areas, highly crushed aggregates having angles of internal friction of 50° or higher are not available, or are very costly to produce. In such cases, the question arises of how the stability of the less stable but readily available pit-run and crusher-run gravels can be improved. Figure 56(c) demonstrates that the desired increase in stability might be obtained by adding a bituminous binder to introduce cohesion c into the inferior aggregate. For a cohesionlesss aggregate with an angle of internal friction ϕ of 40°, if the addition of bituminous binder develops cohesion c = 2.62 p.s.i., Figure 56(c) shows that only 7.2 inches of base course would be required. Consequently, for the conditions illustrated by Figure 56, a bituminous bound base course 7.2 inches thick, for which ϕ = 40° and c = 2.62 p.s.i., develops the same ultimate strength, 112 p.s.i., for the flexible pavement structure as a whole, as the same thickness of cohesionless aggregate having an angle of internal friction of 50°. In this case, using a bituminous binder to introduce cohesion c = 2.62 p.s.i. into an inferior cohesionless base course material for which ϕ = 40°, confers on it the same strength or stability as that developed by a high quality, highly stable, base course aggregate for which ϕ = 50°.

Verification of the practical value of the addition of bituminous binders for increasing the stability of inferior cohesionless aggregates, is provided by the remarkable strength of sand-bitumen base and surface courses as compared with the instability or lack of strength of the dune, beach, etc., sands from which the sand-bitumen mixtures are frequently made. This principle has been successfully applied in the construction of sand-bitumen base courses for roads or airports in Nebraska (27), Florida (28), and elsewhere (29, 30).

Influence of Greater Thicknesses of Bituminous Pavement

The W.A.S.H.O. Test Road report (14) has pointed out the greater strength and superior performance of a flexible pavement of given total thickness when the depth of the bituminous surfacing was increased from 2 to 4 inches. Figure 57, based upon an ultimate strength approach to flexible pavement design referred to earlier (26), indicates that this is to be expected. When the total thickness of base and surface is 10 inches, Figure 57 indicates that the overall ultimate strength of the flexible pavement structure for the conditions illustrated, is increased from 145 p.s.i. to 200 p.s.i., when the thickness of bituminous surface is increased from 2 to 4 inches.

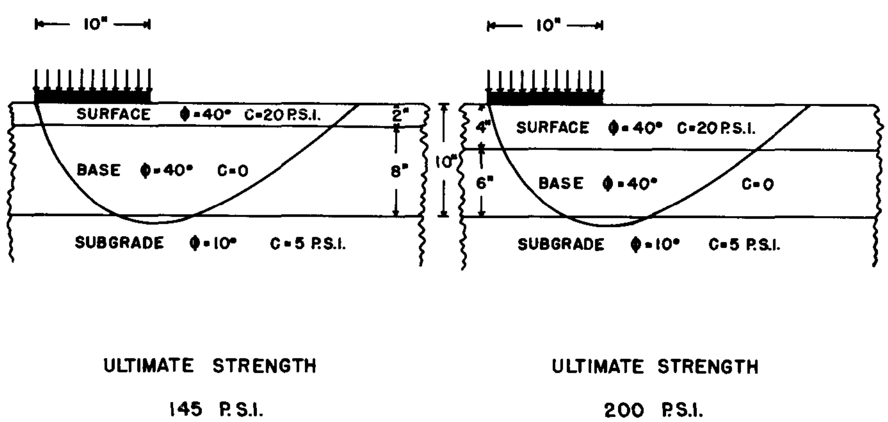

Fig. 57. Influence of Asphalt Surface Thickness on Ultimate Strength For a Given Total Thickness of Surface and Base.

It is to be emphasized in this connection, that increasing the thickness of the bituminous surface itself can only be justified, when the needed increase in overall strength can be obtained more cheaply by increasing the thickness of the bituminous surface, than by increasing the thickness of the granular base.

Incidentally, the W.A.S.H.O. Test Road results, and Figure 57, provide firm evidence in addition to that already presented in connection with Figure 56, that by incorporating controlled quantities of bituminous binder into granular base course materials, the overall bearing capacity of a flexible pavement structure can be materially increased. On sections of the W.A.S.H.O. Test Road where the overall thickness of base and surface was 10 inches, for example, the asphalt surface was 2 inches thick on one tangent of each loop and 4 inches thick on the other tangent of each loop. In this case, all four 10-inch test sections could be looked upon as having a 2-inch asphalt surface, while two of the 10-inch test sections also had a 2-inch bituminized base. The striking difference in strength and performance observed for these sections under actual traffic tests, was due to the existence of the 2-inch bituminized base in one case (the 4-inch surface), and to its absence in the other (the 2-inch surface). However, a bituminized base can only be justified when the required increase in overall strength can be obtained more cheaply by incorporating a bituminous binder into a portion of the total depth of base, than by employing a greater thickness of granular base course material.

Influence of Paved Shoulders

One of the most important findings of the W.A.S.H.O. Test Road project was the discovery that the outer wheel path of a flexible pavement (near the shoulder) is fundamentally weaker than the inner wheel path (near the centre of the pavement). The ultimate strength approach to flexible pavement design already referred to, (26), indicates that this was to be expected, Figure 58, when the shoulders consist of the usual

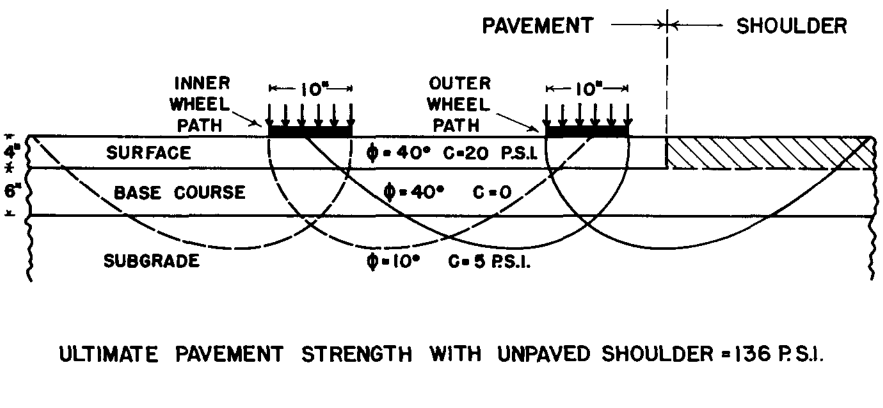

Fig. 58. Influence of Paved Shoulder on Ultimate Strength of Flexible Pavement.

gravel or earth. For the particular conditions illustrated by Figure 58, the ultimate strength of the flexible pavement along the inner wheel path is 200 p.s.i., but is only 136 p.s.i. for the flexible pavement in the outer wheel path. Figure 58 demonstrates that this basic difference in the ultimate strength of the outer and inner wheel paths occurs because the bituminous surface of the outer wheel path serves as a paved shoulder for the inner wheel path. Furthermore, in the absence of moisture or density gradients across the roadway in the subgrade or base course or both, Figure 58 indicates that the strengths of both wheel paths would become identical, 200 p.s.i., if the shoulder were paved, that is, if the bituminous surface were extended over the shoulder. When short lengths of paved shoulders were added to several sections of the W.A.S.H.O. Test Road, traffic tests proved that this increase in strength of the outer wheel path actually occurred.

It is apparent that flexible pavement thickness requirements at the present time are dictated by the thickness needed for the outer wheel path. Since a uniform thickness is usually specified for the entire cross-section, this means that the thickness provided for the inner wheel path represents considerable overdesign.

As a first impression, highway engineers may feel that paved shoulders would add considerably to the overall cost of a highway project. However, by adding a paved shoulder, the thickness for the outer wheel path could be appreciably decreased. This would result in a substantial reduction in the present flexible pavement thickness requirements for highways. For the particular conditions at the W.A.S.H.O. test site for example, the W.A.S.H.O. Road Test Report (14) indicates that for any heavy axle load supporting value, the base course thickness could be reduced by about 4 inches if the shoulders were paved. An appreciable reduction in base course thickness, particularly when the full depth of base extends over the entire cross-section, might be sufficient to pay for a large portion or even the entire cost of paved shoulders. In addition, the intangible, but very positive value of firm paved shoulders to motorists in general merits consideration.

GENERAL

In this section, two items of more general interest with respect to flexible pavement thickness requirements will be covered.

Relative Quality of Sub-base and Base Course Materials

The highest shearing stresses occur in the immediate vicinity of the loaded area, and their intensity decreases with increasing depth and distance from the wheel load. Consequently, where there is some choice of sub-base and base materials, those of lowest stability, such as sands, inferior pit-run gravels, etc., should be placed immediately over the subgrade as the lowest layer of the sub-base. Successive layers of materials of increasing stability should follow in order from bottom to top. The most stable aggregates should be employed for the base course to the depth of the minimum thicknesses shown in Figures 18 and 19.

If both sub-base and base course materials are to come from a natural gravel deposit, pit-run gravel all passing a 3-inch square screen may be used for the sub-base, but selected crusher-run gravel should be specified for the base course to the depth of the minimum thicknesses shown in Figures 18 and 19.

If the only sub-base and base course materials available, are the crushed gravels or crushed stone ordinarily employed for the base course, these must be used for the full depth of flexible pavement indicated by the traffic, climate, and other conditions associated with the project. No reduction in thickness should be made even if granular materials of excellent quality are employed for the full depth required.

To develop their inherent stability, sub-base and base course materials must be compacted to high density during construction. In general, a minimum of 100 per cent of standard A.A.S.H.O. maximum density should be specified for sub-bases and base courses for highways, while the corresponding minimum sub-base and base course densities for airports should be 100 per cent of modified A.A.S.H.O. maximum density. For some aggregates, the degree of compaction shown for them by laboratory density tests cannot always be duplicated in the field with actual construction equipment. Consequently, it is preferable to employ trial test sections made with materials proposed for use on the job, to determine the percentage of laboratory compaction that can be obtained with a reasonable number of passes of rolling equipment in the field.

Strengthening an Existing Flexible Pavement

Because of higher wheel loads, or a much greater volume of traffic, than originally anticipated, it is frequently necessary to strengthen an existing flexible pavement.

Whenever the grades, drainage, and other conditions permit, if the existing flexible pavement is in reasonably good condition, it should be preserved intact, and the new construction should be superimposed over it. Because of compaction by traffic, and elimination of weak areas by maintenance over the years, the old flexible pavement structure will usually be much stronger than the same thickness of new material. At the relatively low temperatures that will prevail after it has been covered over, each inch of thickness of the existing bituminous surface is equivalent in load supporting value to several inches of granular base, as the results of the W.A.S.H.O. Road Test have so clearly indicated (14).

If the subgrade for the old flexible pavement was properly designed and constructed, the existing pavement surface should be taken as the subgrade for the new construction. Plate bearing tests conducted on the surface of the old pavement will provide the value of the subgrade supporting value to be used to determine by means of Figure 18 or

Figure 19, the additional thickness of new material required for the strength increase considered to be necessary.

When the additional thickness needed is substantial, it should consist of a layer of granular base course material of excellent stability followed by a new bituminous surface. The Canadian Department of Transport has used this method very successfully for strengthening existing runways, taxiways, etc. It is important that the surface of the old pavement have sufficient crown or gradient, to provide positive and adequate drainage for the removal of any water that may find its way into the layer of granular base course material between the old and new bituminous surfaces.

When the required increase in strength is not too large, it can often be obtained most easily by placing an additional layer of bituminous concrete over the existing bituminous surface. An illustration of the effectiveness of an added layer of bituminous concrete for this purpose is given in Figure 59 taken from an earlier paper (26). If for the conditions illustrated in Figure 59, the existing flexible pavement consisted of 2 inches of bituminous concrete on 6 inches of granular base, its

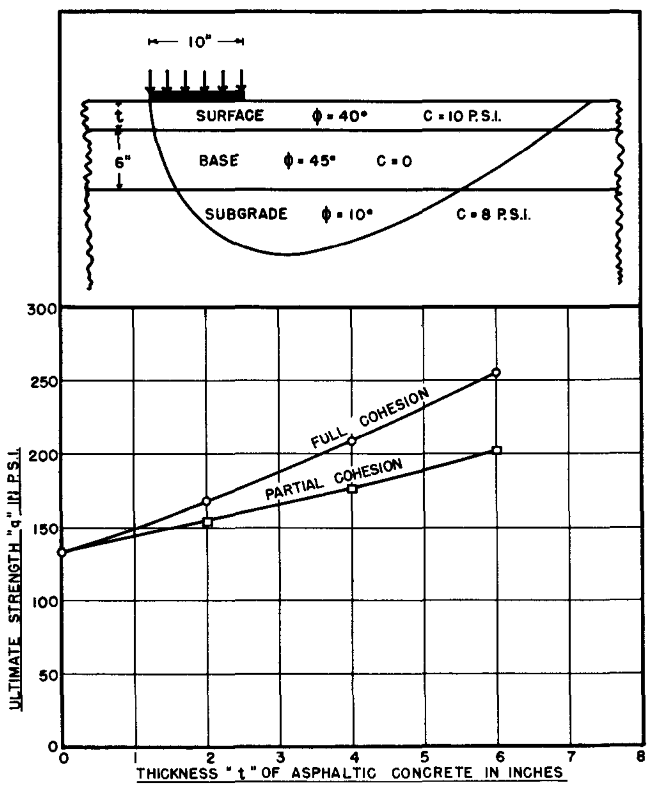

Fig. 59. Influence of Thickness of Asphalt Surface on the Ultimate Strength of a Flexible Pavement.

ultimate strength can be seen to be 168 p.s.i. By adding another 2-inch layer to bring the thickness of bituminous concrete to 4 inches, the ultimate strength of the entire flexible pavement structure would become 208 p.s.i., an overall strength increase of 24 per cent. Finally, if 4 inches of bituminous concrete were added to bring the total thickness of bituminous concrete to 6 inches, the ultimate strength would become 255 p.s.i. in this particular case, for an overall strength increase of 52 per cent.

Figure 59 also demonstrates that a layer of well-designed bituminous concrete provides a much greater increase in the strength of a flexible pavement structure, than the same thickness of granular base. For example, the ultimate strength of the flexible pavement with 6 inches of granular base illustrated at the top of Figure 59, is 134 p.s.i. when the thickness of the bituminous concrete surface is zero. The addition of a 4-inch layer of bituminous concrete increases the ultimate strength to 208 p.s.i., a gain of 55 per cent, while an additional 4 inches of granular base increases the ultimate strength to just 162 p.s.i., an overall strength increase of only 21 per cent.

Figure 59 demonstrates that overlays of properly designed bituminous concrete can be very effective for increasing the ultimate strength of flexible pavements that are beginning to show signs of distress due to overloading. Nevertheless, whenever a large increase in strength is required, an economic study should be made to determine whether the necessary strength increase could be obtained more cheaply by a layer of granular material and a bituminous concrete surface, or by a greater thickness of bituminous concrete without a layer of granular aggregate. When a very large increase in wheel load supporting value is required, it is almost invariably necessary to employ the combination of a layer of granular material of considerable depth with a wearing surface of bituminous concrete of normal thickness.

Summary

1. Because of the important influence of subgrade strength on flexible pavement thickness requirements, seven fundamental principles of subgrade design and construction are briefly reviewed.
2. Brief reference is made to an investigation of the strengths of airport runways by means of plate bearing tests conducted by the Canadian Department of Transport.
3. Data are presented to show how the strength of the subgrade and of the overall flexible pavement structure varies with the size of the loaded area.
4. Charts of design curves for both airports and highways are provided, showing the minimum thickness of flexible pavement required to carry any wheel load over any subgrade.
5. A chart of design curves is included for flexible pavement thickness requirements for parking lots, loading and unloading areas, etc., for stationary highway wheel loads.

6. The influence of impact, and of eccentricity of axle loading, on flexible pavement thickness requirements, is considered.
7. Charts are presented that enable the reduction in flexible pavement thickness to be determined when trucks are equipped with dual wheels, and when the landing gear on aircraft consist of dual or dual tandem wheel arrangements.
8. A method for establishing the load on tandem axles of any spacing on highway vehicles, that is equivalent to a single axle load, is presented.
9. A method for determining the influence of traffic volume, and of the wide range and number of various axle weights per 1000 vehicles of average traffic, on flexible pavement thickness requirements is described.
10. A procedure is presented for determining the effect of frost action and climate on flexible pavement thickness requirements.
11. The influence of braking stresses, quality of base course material, thickness of bituminous pavement, and paved shoulders, on the required thickness of flexible pavements, is demonstrated.
12. Procedures for determining the additional thickness of material required for strengthening an existing flexible pavement are described.

Acknowledgments

The subject matter of this paper has resulted from part of an extensive investigation of airports in Canada, that was begun by the Canadian Department of Transport in 1945. Air Vice-Marshall A. de Niverville, Director of Air Services, has the general administration of this investigation. It comes under Mr. Harold J. Connolly, Chief Construction Engineer, Mr. George W. Smith, Assistant Chief Construction Engineer, and Mr. D. A. Lane. In their respective districts, the investigation is carried on with the generous cooperation of District Airway Engineers G. T. Chillcott, E. B. Wilkins, L. Millidge, R. A. Bradley, F. L. Davis, and W. D. G. Stratton.

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APPENDIX

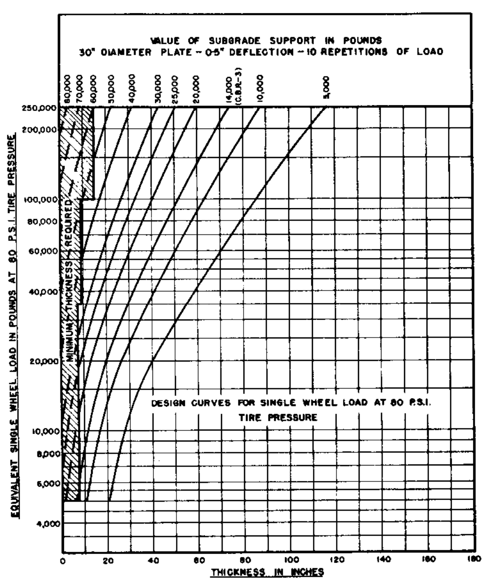

Fig. 24. Flexible Pavement Design and Evaluation Chart for Single-Wheel and Multiple-Wheel Landing Gear Assemblies (Tire Pressure 80 P.S.I.).

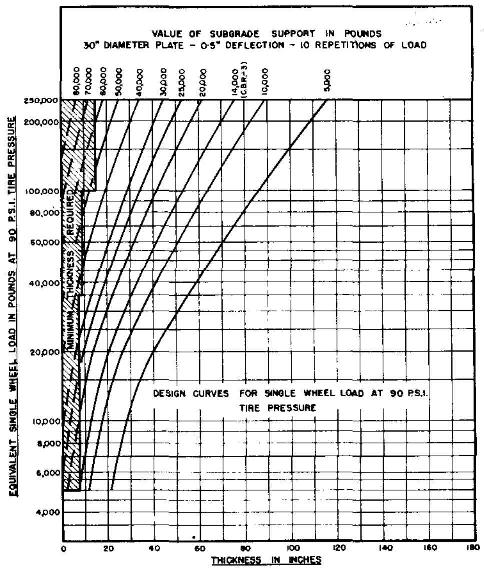

Fig. 25. Flexible Pavement Design and Evaluation Chart for Single-Wheel and Multiple-Wheel Landing Gear Assemblies (Tire Pressure 90 P.S.I.).

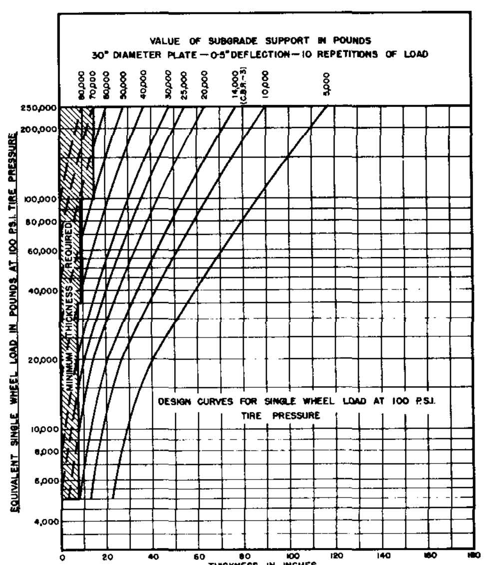

Fig. 26. Flexible Pavement Design and Evaluation Chart for Single-Wheel and Multiple-Wheel Landing Gear Assemblies (Tire Pressure 100 P.S.I.).

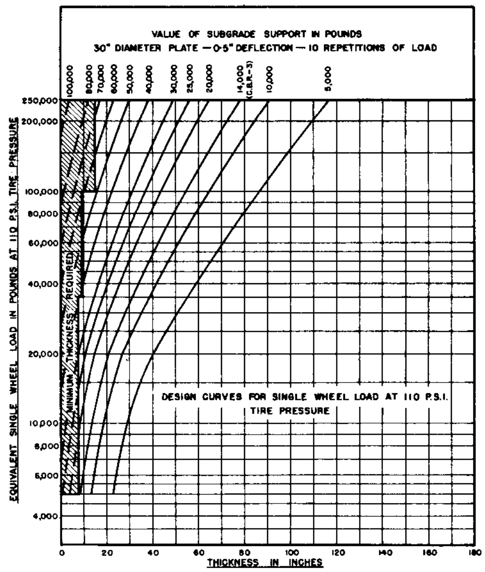

Fig. 27. Flexible Pavement Design and Evaluation Chart for Single-Wheel and Multiple-Wheel Landing Gear Assemblies (Tire Pressure 110 P.S.I.).

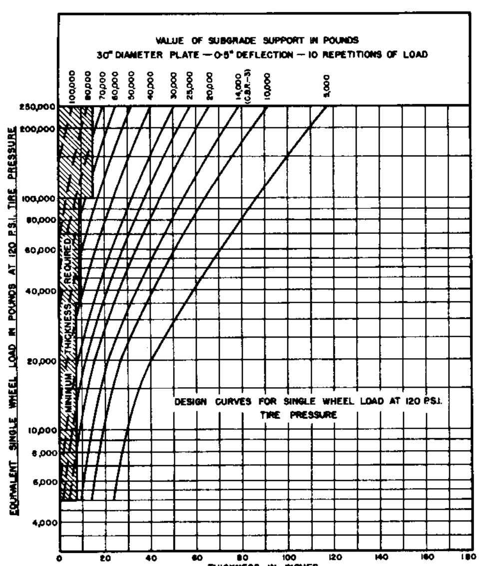

Fig. 28. Flexible Pavement Design and Evaluation Chart for Single-Wheel and Multiple-Wheel Landing Gear Assemblies (Tire Pressure 120 P.S.I.).

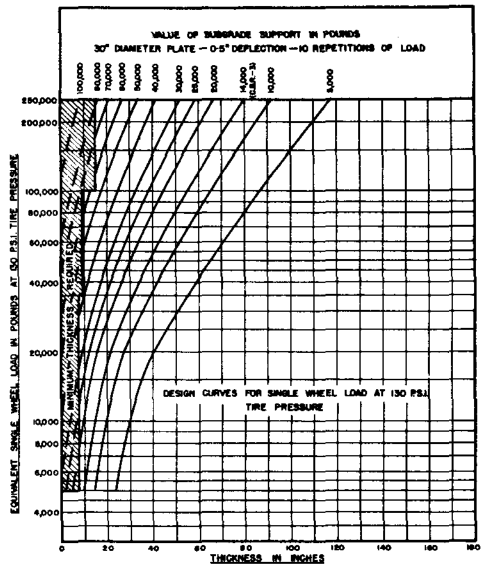

Fig. 29. Flexible Pavement Design and Evaluation Chart for Single-Wheel and Multiple-Wheel Landing Gear Assemblies (Tire Pressure 130 P.S.I.).

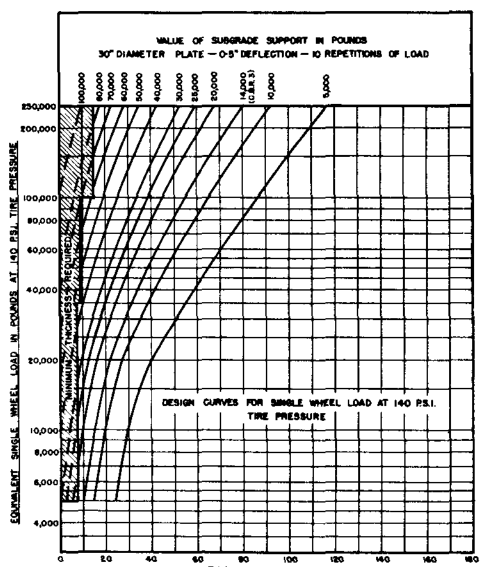

Fig. 30. Flexible Pavement Design and Evaluation Chart for Single-Wheel and Multiple-Wheel Landing Gear Assemblies (Tire Pressure 140 P.S.I.).

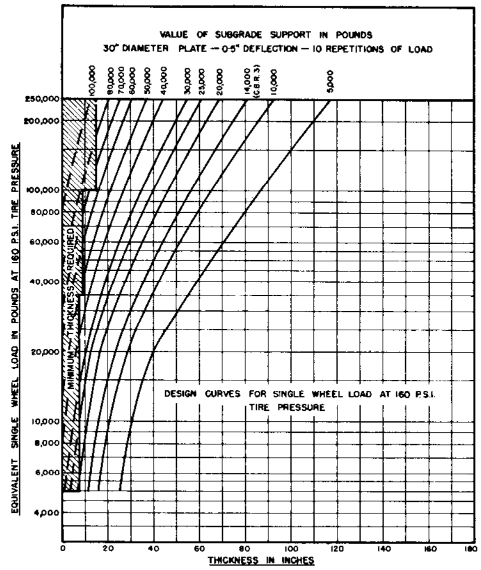

Fig. 31. Flexible Pavement Design and Evaluation Chart for Single-Wheel and Multiple-Wheel Landing Gear Assemblies (Tire Pressure 160 P.S.I.).

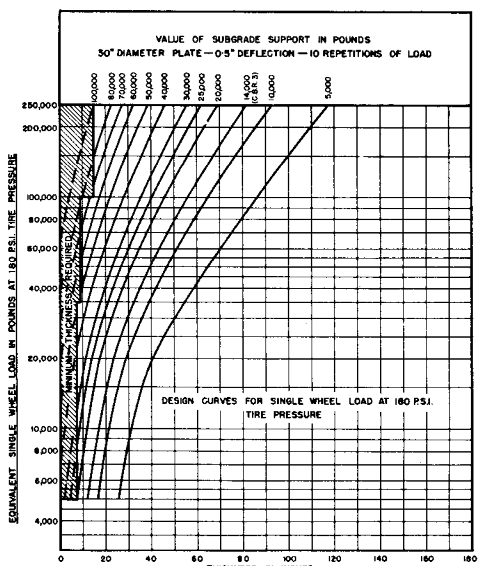

Fig. 32. Flexible Pavement Design and Evaluation Chart for Single-Wheel and Multiple-Wheel Landing Gear Assemblies (Tire Pressure 180 P.S.I.).

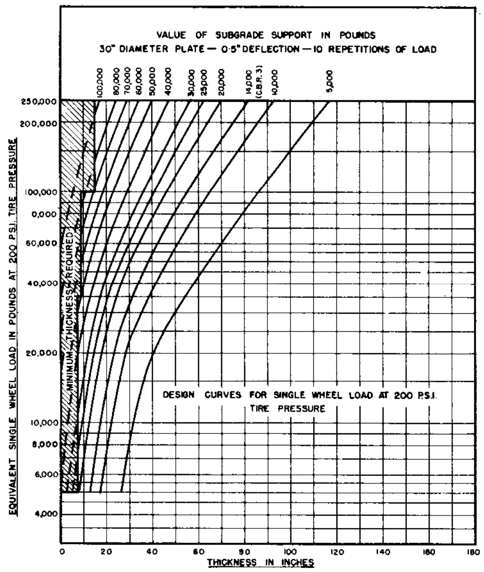

Fig. 33. Flexible Pavement Design and Evaluation Chart for Single-Wheel and Multiple-Wheel Landing Gear Assemblies (Tire Pressure 200 P.S.I.).

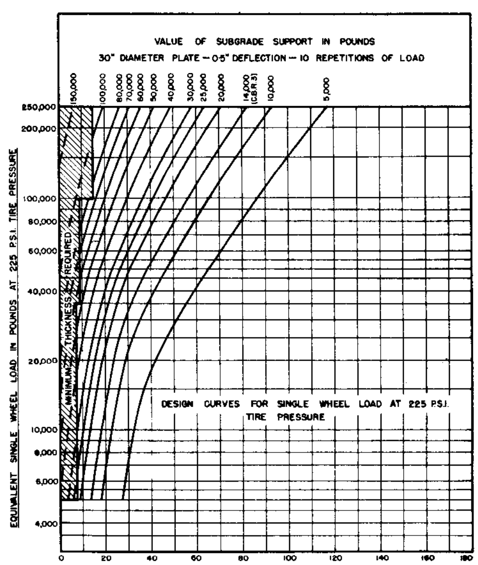

Fig. 34. Flexible Pavement Design and Evaluation Chart for Single-Wheel and Multiple-Wheel Landing Gear Assemblies (Tire Pressure 225 P.S.I.).

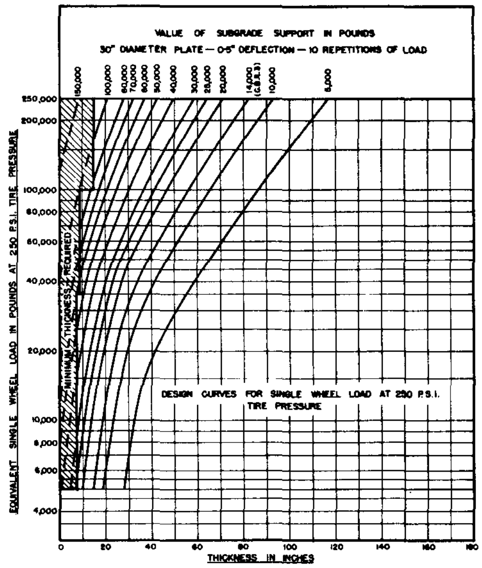

Fig. 35. Flexible Pavement Design and Evaluation Chart for Single-Wheel and Multiple-Wheel Landing Gear Assemblies (Tire Pressure 250 P.S.I.).

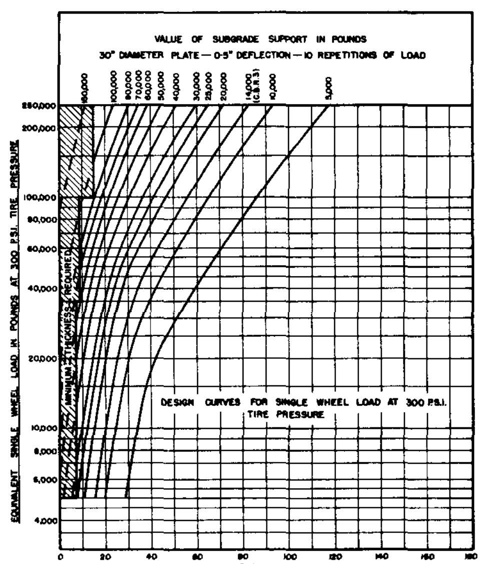

Fig. 36. Flexible Pavement Design and Evaluation Chart for Single-Wheel and Multiple-Wheel Landing Gear Assemblies (Tire Pressure 300 P.S.I.).

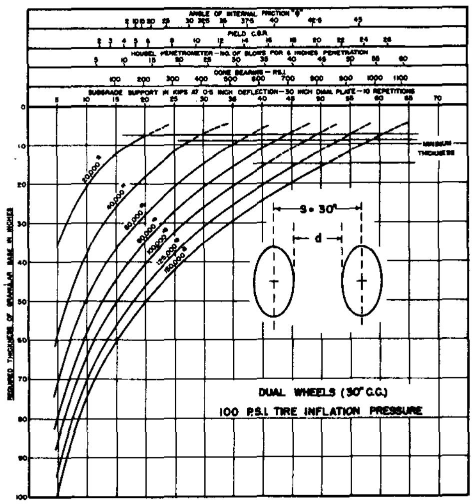

Fig. 37. Flexible Pavement Thickness Requirements for Runways for Aircraft With Dual Wheel Landing Gear (100 P.S.I. Tire Inflation Pressure).

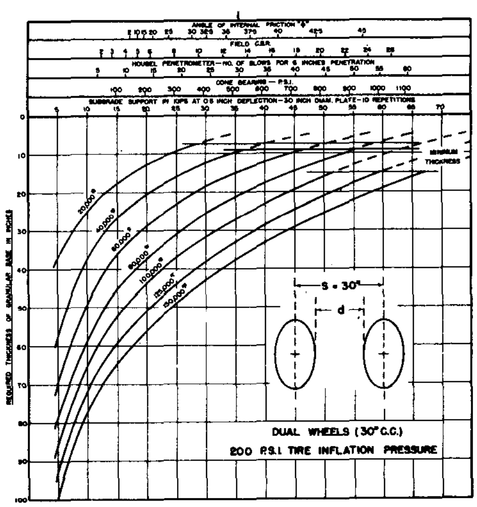

Fig. 38. Flexible Pavement Thickness Requirements for Runways for Aircraft With Dual Wheel Landing Gear (200 P.S.I. Tire Inflation Pressure).

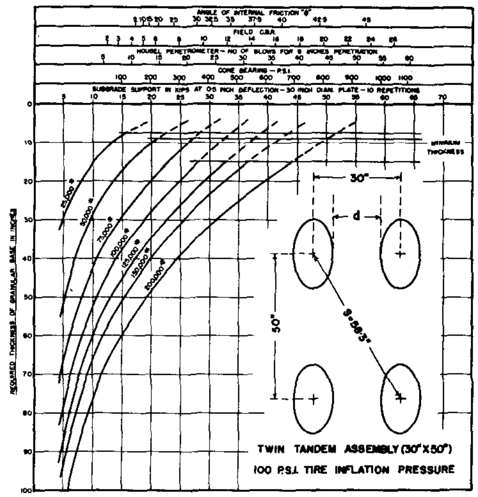

Fig. 39. Flexible Pavement Thickness Requirements for Runways for Aircraft With Twin Tandem Landing Gear (100 P.S.I. Tire Inflation Pressure).

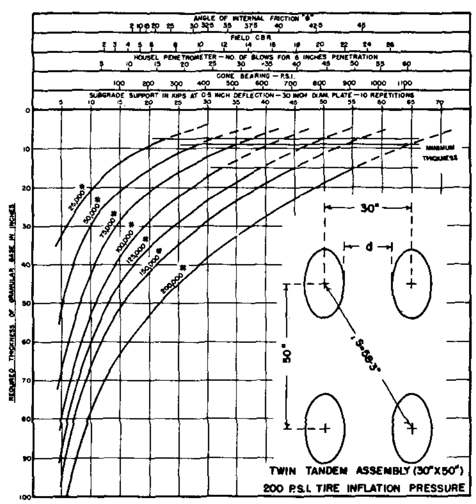

Fig. 40. Flexible Pavement Thickness Requirements for Runways for Aircraft With Twin Tandem Landing Gear (200 P.S.I. Tire Inflation Pressure).

SUMMARY

PROFESSOR W. S. HOUSEL

Following the presentation of the papers by members of the symposium panel it seems desirable to emphasize certain trends in the development of flexible pavement design which may point the way ahead. As Professor Hennes put it so aptly, the real need is for a design method by which we can extrapolate our experience and knowledge to meet the demand for a more rational method of designing flexible pavements. This method must provide a common basis of comparison for design practice not only in this country but everywhere that engineers are looking to our technological development for some guidance. That is the real objective of flexible pavement design.

The question may well be asked. What are the requirements of an adequate method of design? In the first place it must be fundamentally sound, which is to say that it must be formulated in terms of the basic principles or structural theory which permits a logical and realistic treatment of the variables involved in the behavior of flexible pavements. Empirical methods may serve only as temporary expedients so long as our knowledge of the various factors is inadequate. At the present time there is much confusion due to a failure to separate those factors which still require empirical treatment from those which may be handled on a rational basis.

The experience reported by a number of the state highway departments at a meeting of the Highway Research Board some two years ago illustrates this state of affairs. In 1946 and 1947 a number of state highway departments put into practice certain definite procedures for designing flexible pavements which represented the best judgment of the responsible design engineers of those states. These methods in general included definite test procedures that were selected to measure subgrade bearing capacity, the strength or load distributing ability of the various components of the pavement structure. For example Wyoming, Colorado and Virginia all selected the CBR as the basic test, Texas and Kansas selected triaxial compression, North Carolina chose plate loading tests and Missouri took the group index which is computed from routine laboratory tests of soil characteristics.

In addition to these physical tests empirical factors were introduced to place a quantitative value on environmental factors such as drainage and frost action. Traffic volume and magnitude of wheel loads were also expressed in terms of equivalent wheel loads and a numerical coefficient introduced into the thickness formulae to cover traffic characteristics.

The attempt to include in pavement design all physical factors and environmental conditions which affect pavement performance is to be commended. However, the statistical procedures which have been used are an attempt to compound unlike elements in an integrated statistic which fails quite completely to provide any reasonable resemblance to the basic concepts of structural behavior of a flexible pavement. You cannot average cats and dogs and by the same token you cannot combine traffic statistics with the physical properties of material as measured by a triaxial compression test or any other precise procedure.

The experience of the state highway departments illustrates the difficulties that are bound to develop in such an attempt. After a trial period of some 6 or 7 years the states reported their experience with these methods. In all states pavement performance surveys showed that there had been an improvement due to the use of definite design procedures, but failures were still too prevalent. In other words the standard design had proved in most cases to be deficient and this was generally ascribed to an unanticipated increase in volume of traffic and the percentage of heavier commercial vehicles.

The important point was, however, that as a result of this experience all agencies were forced to revise these methods but no common basis for doing so could be found. Some proposed a revision of test procedures, others wished to change the empirical coefficients that were being used and some proposed an arbitrary change in thickness. The discussion became a demonstration that no single method or combination of several provided a common basis for extrapolating this common experience.

It was then suggested that the ultimate objective might be accomplished in two separate steps by considering first, the structural mechanics of a flexible pavement structure and, second, modifying the design empirically to fit the environmental conditions and severity of traffic loading. The first phase of this problem could be reduced to definite quantitative measures of the physical properties of the structural elements by accepting any one or combinations of well known test procedures reasonably representative of the structural behavior of a flexible pavement. This procedure could produce comparable and reproducible results by all testing laboratories which when incorporated in a generally accepted thickness formula would produce a common design.

It was suggested that this design be developed as a common reference or standard such that no failure would occur under any combination of environment or traffic loading. This would represent a 100 per cent design which might very well be too heavy and too expensive for all but the highest type of road under the most severe combination of use and field conditions. For less severe conditions and for purposes of economy any selected project might be set up for 50, 60 or some other proportion of the 100 per cent design standard. Thus under stage construction or varying requirements reasonable adjustments could be made to meet any combination of conditions without upsetting the basic test procedure or design methods. Experience in different areas under different conditions could then be compared on a common basis. Eventually the cumulative experience in pavement construction and performance could be more readily extrapolated to new and changing requirements.

This suggestion was favorably received at the Highway Research Board and is introduced in the present symposium in the hope that it may serve to direct the subsequent discussion toward a more definite objective.

Discussion

PROFESSOR HOUSEL: Mr. Chairman, before we ask for the first question I wanted to refer very briefly to the summary which was presented at the end of the first period.

A very good friend of mine once said in discussing scientific research, that the object of a research investigation is to isolate the responsible variables and systematically determine their relative importance. That, gentlemen, is exactly what members of the panel have tried to do in this symposium and we hope that you will be able to help us to realize that objective in the succeeding discussion with your questions or comments. The meeting is now open for such questions and comments from the floor.

MR. BERNARD A. VALLERGA: During the panel presentations this afternoon I was trying to phrase some questions to ask the panel. It ended up with an outline of questions which just about covers the entire field of paving design. I took the liberty during the intermission to talk to Professor Housel and tell him what I had in mind.

I have drawn on the blackboard on the left-hand side a sketch of a typical pavement section that consists of a subbase, base, and surfacing with a wheel on the surfacing, and over on the right listed: Load, number of repetitions and tire pressure.

I have questions to ask as follows: Assuming that we know the load, the number of repetitions and the tire pressure, the first question is: What properties of the subgrade soil must be measured, and how?

Second question: Assuming the properties of the subgrade soil can be evaluated, say, reasonably accurately evaluated, how or by what method or procedure should the thickness of subbase, base and subgrade material be determined, and which factors should be taken into consideration?

Three: What quality of material is necessary at each level, and how should it be measured and controlled?

Four: What about fatigue properties of soil and surfacing materials?

Five: How should climatic conditions be incorporated in a thickness design method?

Now I realize this is a complex question. I have asked my questions. I am hoping to get answers to them, at least partially if not completely. I would like to give this outline to Professor Housel to handle any way he sees fit.

PROFESSOR HOUSEL: It would appear that Mr. Vallerga's list of questions pretty well covers the entire subject. However, it comes as no surprise to me at this time as these questions were discussed during intermission. I think they make an excellent outline for us to use in our subsequent discussion. I think possibly we might take several of these questions and then later give others from the floor an opportunity to ask other questions.

Now, to take the first question which was: What properties of the subgrade soil shall be measured, and how?

Professor Hennes, how would you like to take that question?

PROFESSOR HENNES: I don't think I have an answer. I have a point of view.

PROFESSOR HOUSEL: You might say that would be true of all of the answers.

PROFESSOR HENNES: Actually I think it would be useful to split the problem into several components. Not only do subgrades vary but in a given subgrade, shear strength might be critical at one level, while compressibility might be critical at another level. The subgrade situation is not much different from the problem confronting the structural engineer in designing a ceiling or floor panel. Both the strength of the floor slab and its maximum deflection are significant. In the matter of subgrade properties also we may be concerned either with ultimate strength or with settlement.

PROFESSOR HOUSEL: I understand, Professor Hennes, that you have said we should measure in some way the ultimate strength or bearing capacity and we should also measure the settlement or deflection at any bearing pressure which we intend to use in design.

PROFESSOR HENNES: Yes. I think that in referring to settlement I should have mentioned that this means concern over the stress-strain characteristics of the material. This can be measured in a number of ways. Several suggestions were made in this morning's program as to how it can be accomplished.

PROFESSOR HOUSEL: Would anybody else on the panel care to comment on that particular question?

DR. McLEOD: Well, certainly, in our territory the loss of strength during the spring break-up period is most important. I had two or three slides to show how we handle that problem in our territory but I ran out of time.

PROFESSOR HOUSEL: Let me suggest, that we stay on this first phase. Let's not get into the second phase which involves environment. Therefor what properties and characteristics exclusive of environment, would you measure?

DR. McLEOD: Stress and strain.

PROFESSOR HOUSEL: Would you measure ultimate strength or do you include that in the stress and strain?

DR. McLEOD: We are definitely interested in ultimate strength as well as stress and strain. We are interested in both the plastic characteristics of the soil and its elastic properties.

MR. GRIFFITH: I am inclined to agree with Professor Hennes on the two points he brings out. I trust that he includes resistance to shear deformation in the strength characteristics he discussed.

PROFESSOR HENNES: I don't think they can be separated.

PROFESSOR HOUSEL: I agree with your combined opinion that you can't separate strength characteristics whether you measure shearing resistance or function of shearing resistance in bearing capacity. I believe there is considerable unanimity of opinion on this first question to the effect that we will measure the ultimate strength or bearing capacity and we will also determine the deflection at various loads, which is to say the stress-strain characteristics of the material involved. We are not discussing various methods of doing that at this time.

Mr. Vallerga, would you care to accept the answers or do you have any comment?

MR. VALLERGA: Could I ask how the panel might take into account elastic rebound in a natural soil material, or do they feel that this also is an important property, and a similar question, do they feel that the swell characteristics of the soil, of the subgrade soil, is an important characteristic?

PROFESSOR HOUSEL: The last question is outside the question of stress-strain relations. The first question, unless the panel disagrees, is included in the stress-strain characteristics or elastic characteristics of the supporting medium, from which it will be possible to evaluate the rebound that might take place upon release of load under repetitive loading. Will you accept that, panel?

PROFESSOR HENNES: Yes.

PROFESSOR HOUSEL: If that completes the first question, the second question may now be considered.

MR. VALLERGA: Professor Housel, under repeated loading, I may have forgotten to say elastic rebounding under repeated loading, not the rebound from one attempt.

PROFESSOR HOUSEL: In answer to that question, Mr. Vallerga, let me say that I would like to refer to a paper I heard at the Highway Research Board at the last meeting just two weeks ago. This paper which had to do with repetitive loading on bituminous mixtures was presented by Professor Goetz and one of his associates. In it they showed some of the most significant relationships I have seen in connection with testing of that kind, and which I think represent a most important line of approach on the very subject which you have now brought up.

They showed that at a certain stage of load you could repeat a given load increment indefinitely and obtain the same elastic deformation, which was recovered as rebound. At a higher load, there would be a slight amount of creep, or a slight amount of permanent deformation. Continued repetition of that higher load eventually produced a fatigue failure on a bituminous mixture.

My own opinion is that we should attempt to determine that load which produces some permanent deformation or that doesn't give 100 per cent elastic rebound. That represents the ultimate load for which we should design if we want a structure which will never fail.

A structure which will never fail may not be economically sound. We might not want to design a structure that heavy, but it could serve as a standard to be approached as an ultimate objective. I believe we are at the present time designing our pavements to fail and eventually they will fail under repeated loading. Perhaps such limitation may be necessary from an economical standpoint, but I would approach it from a different viewpoint. I would try to find the real cause of failure and the load which produced it. As given in this paper by Goetz, this limiting load would be that which produced continued deformation, and that would be the ultimate load in design or bearing capacity of the pavement structure.

PROFESSOR HENNES: I would just like to give vent to my own feeling now that we are talking about fatigue. We talk about it as though it is some sort of mysterious property we haven't evaluated. I don't think it is the same thing in a random material as in a piece of pavement. I think what we are talking about is accumulated in elastic deformation. I don't think in any heterogenous or even in a well-oriented base or subgrade there is any real change in the material after 100,000 repetitions more than after a single load repetition. I don't think there is a weakening, except possibly as a by-product of aggregate degradation.

PROFESSOR HOUSEL: Can we agree that we are now discussing a plastic subgrade, cohesive material? Mr. Vallerga, will you agree with that?

MR. VALLERGA: Gentlemen, I believe you do not quite understand my question. If one has a subgrade soil that under repeated loading deflects excessively and then recovers, this will have an effect on the pavement structure of some kind.

A paper by Hveem presented a year ago at the Highway Research Board, dwelt at great length on this matter of deflections and their effect on pavements, and he has some very graphic data that show that when these elastic deflections are excessive the result is cracking in the pavement surface, even though the pavement is designed adequately from the standpoint of the stress-strain characteristics of the underlying soil.

PROFESSOR HOUSEL: I took it that your question was much more fundamental than that. I feel that the question you have now raised, one of the maximum total deflection that a pavement surface will stand, is another question which has to be handled as a separate problem apart from the ultimate bearing capacity of the subgrade. How about it, panel, do you accept that this is another problem?

DR. McLEOD: Yes.

MR. GRIFFITH: Yes.

PROFESSOR HOUSEL: There seems to be agreement on that. I think we shall now go to the second question and any unsatisfactory results of our discussion of the first question can be taken up in the bar this evening.

We will pass now to the requirements of quality of subbase, base and surfacing. I would like to interpret that to mean, first, the quality requirements of the structure which we interpose between the applied load and the supporting subgrade with a definite bearing capacity. Mr. Griffith, would you like to take that?

MR. GRIFFITH: Are not the basic requirements for these components pretty much the same as for the subgrade? These are, for example, ultimate strength requirements which naturally are somewhat greater than for the subgrade. There are also limitations on stress-strain characteristics of these components. There are limits on the amount of strain which a pavement surface may withstand without cracking and I believe this is the point Mr. Vallerga was trying to bring out.

Apparently he is thinking of pavements with high defection characteristics such as are sometimes found in micaceous subgrades. I would say that the requirements for subbase, base and pavement are basically the same as so aptly described by Professor Hennes for subgrades.

PROFESSOR HOUSEL: Let Mr. Hennes aptly repeat what he said.

PROFESSOR HENNES: That is the most embarrassing question that has come up this afternoon. I am at a loss to repeat what I so aptly said, except that I think that I expressed a point of view that subgrade and the base, although of different components, have about the same requirements, qualitatively, that they have to be strong enough and shouldn't deflect too much.

I could go on to say I think it is possible that these repetitive loadings don't necessarily have to be measured by repetitive tests. A material which exhibits excessive strain under a single load probably will experience excessive strain under repetition of loads also.

PROFESSOR HOUSEL: Dr. McLeod, would you care to comment on this question of the quality requirements of the flexible structure itself?

DR. McLEOD: It is my belief that two points must be kept in mind insofar as the selection of base course material is concerned. First of all, we are interested in thickness, and secondly, we are concerned that the quality of the base course material will insure sufficient shearing strength that failure will not occur within the base course itself. A minimum thickness is needed to avoid failure within the subgrade. The flexible pavement must be thick enough that the subgrade will not be overloaded and fail.

The second criterion concerns the quality of the base course material. Tire inflation pressures on jet aircraft today exceed 300 psi., and the base course material must be capable of developing sufficient shearing strength to resist the high unit wheel load pressures applied to the surface of the pavement.

With regard to protecting the subgrade from failure, hundreds of plate bearing tests conducted by the Canadian Department of Transport have indicated that there is no dependable difference in granular base materials in this respect.

We were rather surprised to have this result develop from our plate bearing test data, although it had been a design criterion of the Corps of Engineers for some time. I believe I am quoting them correctly when I say as far as their thickness curves are concerned they make no allowance for difference in base course quality. The flexible pavement thickness requirements of the Department of Transport are also independent of base course quality.

PROFESSOR HOUSEL: We haven't heard yet from Mr. Marshall, so perhaps he ought to have an opportunity to discuss this question.

MR. MARSHALL: Just to let you know I am still here and still concerned about the practical aspect of this thing, whatever methods we finally wind up with to determine these desirable characteristics of subgrade and base and subbase materials, they have got to be something that we can handle expeditiously.

When we are talking about, as Ohio is now, constructing some 500 projects a year, the methods that we use to evaluate these things have got to be such that they can be worked pretty rapidly.

PROFESSOR HOUSEL: Thank you, Mr. Marshall. I don't feel that the panel has answered the question, but, of course, we are all simply expressing points of view up here.

MR. J. O. IZATT: Professor Housel, I wanted to get in a word or two here before you relegated the treatment of the base and subbase material to the barroom also.

I was sitting over there wondering if I would get a chance to comment on subgrade soils. I am very happy to hear these gentlemen are pretty much agreed that a fundamental property might be described in simple stress-strain relationships. These relationships are fundamental to an engineer. Many of the other properties might be quite empirical. I would like to offer again as we did this morning, one mechanical means of creating stresses and measuring corresponding strains, and that is with the dynamic testing machine. We apply a load which is put on in many repetitions. We can vary the cycles of loading from as low as 10 to as high as 60 cycles per second. We can also otherwise vary the magnitude of the load and we can measure deformation of the material underneath these loads.

Now it is only a matter of the physical dimensions of the machine which keep it from being used for measuring subgrade soils which are strong enough to comply with Dr. McLeod's seven requirements. We have measured strong soils in terms of these stress-strain relationships. We have also measured many stiffness values on bases and subbases.

It was pointed out this morning that we have developed some of these simple, fundamental relationships. We don't know exactly where we go from here but we do have this one means.

PROFESSOR HOUSEL: Thank you, Mr. Izatt. The panel hasn't finished with the second subject under discussion and one thing is the quality requirement of the paving materials. If I understood Dr. McLeod in the presentation of his paper, he indicated that thickness requirements were independent of the physical property or quality of the base course material. Now he has, in answering the question, said they must be stable against displacement under load, and at the risk of renewing an argument of many years I will say that I think he was referring to internal stability in that particular case as well as shearing resistance.

Then there is another question: Considering the ability of the subgrade to transmit pressure or to relieve the subgrade of concentrated pressure, is that not dependent on the quality of the materials in the flexible pavement? I am passing that one to you, Dr. McLeod.

DR. McLEOD: We have looked at this problem theoretically and on a theoretical basis a very good case can be made for the reduction in thickness of flexible pavements, when base course materials of superior quality are employed. However, against this, we have the results of a larger number of plate bearing tests conducted on actual runways in service. For any given thickness, these indicate that the usual granular base course materials are essentially all alike insofar as protecting the subgrade is concerned, and that no change in base course thickness could be justified on the basis of differences in base course quality.

We know, for example, that the stability of a granular base course material depends not only on angularity of particle shape and roughness of surface texture, but also on density. Apparently our present field compaction equipment is unable to compact these materials to the densities they must acquire if they are to develop in the field the high stabilities that can be demonstrated for them in the laboratory. The angular shape and rough surface texture of the particles causes them to resist compaction to high density. On the other hand, the more rounded aggregates of less inherent stability attain a relatively high density under the usual field compaction effort. The higher relative density of the inherently less stable aggregates seems to compensate for the lower density of the potentially more stable aggregates, so that both develop about the same actual stability in the field. At least, this is implied by our plate bearing tests.

PROFESSOR HOUSEL: I take it, then, Dr. McLeod, that your answer is that the quality of a material does affect its ability to transmit pressure, but it happens what you gain in the case of density on the rounded materials you lose, due to poor interlocking, and vice versa when you have better interlocking and mechanical stability, and you lose density so they offset each other. You recognize the principles that are involved, nevertheless.

DR. McLEOD: I recognize the principles that are involved but the way our plate-bearing tests are being conducted we are unable to reach any conclusions about the way in which load is transmitted through base courses to the subgrade. However, our plate bearing tests imply that the base courses of various aggregates we have investigated, base courses that have been in service for a number of years, perform very much alike in the manner in which they transmit normal loads to the subgrade. Consequently, regardless of what various theories and laboratory tests may indicate, insofar as flexible pavement thickness is concerned, I can only conclude that the supporting values of various base course aggregates per unit thickness are approximately the same. The principal exception to this is when a bituminous binder is introduced into the aggregate. This appears to have a definite strengthening effect as the WASHO Road Test has demonstrated.

PROFESSOR HOUSEL: There is just one more comment that I have to make. On the left-hand side of that board you see a diagram of a load on a flexible pavement in which you have what may be called a normal pressure distribution curve at the subgrade level which can be expressed in terms of an angle of pressure distribution. There is also another curve with a high peak of stress in the center which is concentration of pressure under the load. In all the investigations of pressure distribution I have ever seen there is evidence that at certain ranges of load you have both of those characteristic curves, one of which represents the inability of the material to transmit the pressures in the normal fashion.

Such pressure distribution is cited to support the view that the quality requirements do mean something.

These are the matters I had in mind in answer to Mr. Vallerga's question. I feel we must now pass on to something else.

CHAIRMAN NEVITT: I just couldn't pass. This quality thing I think is subtle when you bring in the fact that quality isn't one test alone, as Dr. McLeod pointed out. I would say the gradation, and so on, in other words, you can get this quality inherent in the material you have but you have to use it. Quality isn't a term of a test, CBR machine or something like that.

PROFESSOR HOUSEL: That seems to have agreement. Dr. Mack?

DR. CHARLES MACK: As the Chairman, Professor Housel, has pointed out, the panel members of the symposium differ in their opinions on the design of bituminous pavements. I have nothing to do with design, so I am not biased. There is apparent agreement, that the stress-strain relationship and the effect of repetitive loading are of importance for the design of flexible pavements. However, no emphasis has been laid on the type of the stress-strain function. It is exactly the type of this function which determines whether or not the effect of repetitive loading is of any consequence.

The types of stress-strain relationships encountered with bituminous pavements are as follows:

1. a linear relationship between stress and strain, representative of elastic behavior;
2. a curvilinear relationship between stress and strain which is convex towards the strain axis;
3. a curvilinear relationship between stress and strain which is concave towards the strain axis.

For a freshly laid and compacted bituminous pavement, the elastic region is of minor importance, and the stress-strain relationship is a combination of the second and third type (Fig. A). Between A and B,

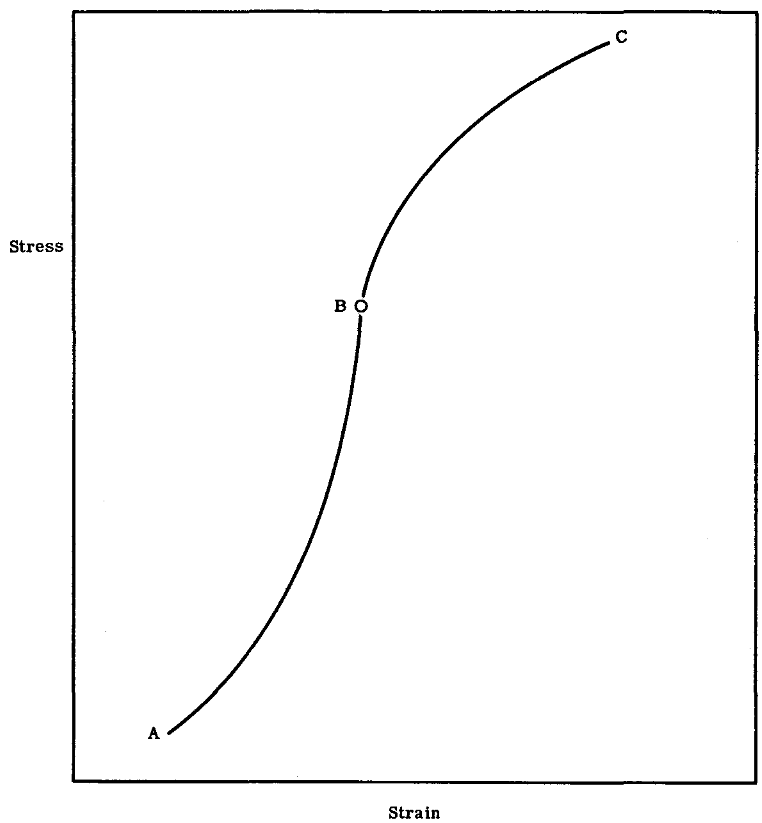

Fig. A.

the curve is convex towards the strain axis. For a given stress increment, the corresponding strain increment decreases with increasing stress. In this region, the pavement requires a resistance to deformation and is in a state of hardening. Between B and C, the strain increases proportionally more than the stress, and the pavement is in a state of progressive weakening.

Curvilinear stress-strain relationship are typical of plastic behavior, and the strain is not only a function of stress but also of time. A constant load applied in the region of hardening (along AB) causes a strain, which increases with time and finally comes to a stop at a certain time t. Since time is additive, the plastic deformation will cease under repetitive loading, when the product of the number of load applications and time of contact is equal to t. To obtain another increment in plastic strain, the load must be increased. Finally, at a load corresponding to the stress at point B, the plastic deformation comes to a stop, the pavement has obtained its maximum amount of hardening and behaves like a solid body. After such a pretreatment, the pavement deforms only elastically within a region of stress which has the stress at B as upper limit, and repetitive loading has no effect on permanent strains.

Along BC, the pavement is in a state of progressive weakening. A constant load applied in this region will cause failure after a certain time, and repetitive loading leads to the same result after the same cumulative time. The time for failure decreases, however, with increasing load. Thus, the stress at point B is of special significance. It represents the upper stress of a region in which a pavement acquires "stability" in its true meaning of the word, and may be called bearing strength. It is a constant characteristic of the pavement at a given temperature. The bearing strength is also the stress at which a pavement receives its maximum densification. At greater stresses the density decreases again.

The design of bituminous pavements should be based on the bearing strength, and the maximum load per unit area, experienced on the road, should not exceed the bearing strength. The same concept applies also to the base course and subsoil. There are cases, however, where the pavement can be under-designed and will not fail, if the amount of heavy traffic is a small portion of the total. Stresses in excess of the bearing strength, submitted to the road surface by heavy traffic, will cause some damage, but subsequent light traffic with stresses less than the bearing strength will revert the pavement from the region of weakening to the region of hardening and will heal the damage done.

PROFESSOR HOUSEL: Thank you, Dr. Mack. I think you have given a very fine explanation of elastic behavior and semi-elastic behavior. May I say we have found the same type of behavior in soil as well as bituminous material?

Mr. Campen, I understood you wanted to ask a question or answer one.

MR. CAMPEN: Professor Housel, you have already answered the point I wanted to make, that we must consider the quality of the base in these designs, and I want to say a little.

We have had occasion to build many test sections in connection with port construction, and we find that in selecting the thicknesses necessary to carry a given load, the quality of the base, as expressed by CBR, does have an affect.

PROFESSOR HOUSEL: Very good. I am glad to hear you agree. I can't help but remember what Professor Scholer said at the last meeting of the Highway Research Board. He said you can correct specific gravity and many other things but you can't correct Campen. I am glad he is on our side.

MR. EARL W. KLINGER: I took the liberty of putting the formula for thickness and the values for the constant "K" on the blackboard before this session. Undoubtedly, this formula is familiar to many of you since I originally reported it to the AAPT in 1943.

I find I am more in agreement with Professor Housel and Mr. Campen than I am with Dr. McLeod since we have actually shown an advantage for quality of the individual pavement components in design for thickness required for load support.

The formula for thickness as written on the blackboard is:

$$T^2 = K\left(\frac{FW_1}{W_2} - 1\right)$$

Where T = Thickness of Pavement Component . . . . (in.)
K = A Constant for Type of Pavement Component
F = A Factor for Load and Traffic Conditions
W_1 = Unit Load on Overlying Pavement Component . . . . . (psi)
W_2 = Unit Load on Underlying Pavement Component . . . . (psi)

Note 1: W_1 and W_2 are measured by same size circular plates, at same deflections and under same conditions of load application. (See ASTM Designation D1195.)

Values of Constant K

K = 9 Asphaltic Concrete Wearing Course and Base Course
K = 12 Asphaltic Penetration Macadam Base Course
K = 30 Crushed Aggregate Base Course (EXCELLENT BASE*)
K = 100 Granular Material Subbase Course (GOOD SUBBASE*)
K = 300 Frost-Free Material Subgrade Course (GOOD SUBGRADE*)

Note 2: *These three designations are taken from The Asphalt Institute Manual Series No. 1, "Thickness Design of Flexible Pavements for Streets and Highways."

The above thickness formula is the one I developed to cover the results of the laboratory work reported by Hubbard and Fields. It was published in the Proceedings of the AAPT, Vol. 15, 1943 and was entitled, "A Suggested Method For Analyzing Load Test Data With Respect to Subgrade Support," by Earl W. Klinger. This formula had been used for some time before its presentation to the AAPT and has since been applied to data available from the United States and Canada. Although it was developed from laboratory loading tests on circular plates, it has also been shown to be applicable to data obtained from field loading tests on circular plates.

The introduction of the Load and Traffic Factor "F" has been found to be of value, but it may be noted that it merely has the effect of modifying the load applied to the overlying pavement component. It has also been found that a value of F = 2 is very severe and perhaps represents the worst conditions of load and traffic encountered on turnpikes and similar heavy-load, high-speed, limited-access highways.

PROFESSOR HOUSEL: Mr. Klinger, I want to ask you one question: Do I understand W-1 and W-2 are pressures that are measured by load tests at each specific horizontal plane or is the pressure at the lower level determined from an angle of distribution?

MR. KLINGER: No attempt is made to evaluate the angle of load distribution. The load tests are made as you last stated. Loads are applied at the top of the individual pavement components (wearing course, base course, subbase course and subgrade) using the same size circular plates, the same deflections and the same conditions of loading.

PROFESSOR HOUSEL: I have that straight. Are there any other questions now or comments from the floor?

DR. J. J. HEITHAUS: Maybe my ignorance on these matters causes me to oversimplify the situation, but I think we have some work at hand already which carries us a long way toward a solution to some of these problems. I think there is a high probability this is true theoretically and at least to some extent practically.

We are concerned here especially with the failures of pavements that occur under traffic. That may not be the only cause of pavement failure but it is the only kind with which we are concerned today. The problem here is to determine the relation between the stress applied to the pavement and the ultimate strength of the pavement.

I think that the work of Odemark[1] is very appropriate in this regard. You may recall that Odemark considers a simplified system, a single layer over a uniform supporting base, and he relates the thickness of the pavement, the radius of the loaded area, the elastic modulus of the surfacing, the elastic modulus of the base, the stress actually occurring in the surfacing and the stress that is applied by the vehicle.

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[1] Odemark, N., Meddelande 77 Statens Vaginstitut, Stockholm, 1949. See M. Reiner, "Building Materials, etc." New York, 1954: p. 365.

Complete graphical representations of Odemark's theoretical relationships can be found in the literature. Briefly, they show that the stress in the pavement increases as E_1/E_2 increases, where E_1 is the modulus of the surface and E_2 is the modulus of the base. However, for any given value of E_1/E_2 the stress in the pavement shows a rather pronounced maximum at a certain critical thickness of the surfacing.

It seems to me this is the sort of approach to the problem that is likely to be very profitable. We know the load applied and the radius of the loaded area from the nature of the vehicle, E_1, the modulus of the surface; we can obtain from the calculations of Van der Poël[2] and others, and E_2, the modulus of the subbase we can obtain from dynamic testing. In this case, we want to set the stress in the surface equal to the maximum allowable stress, in other words, the ultimate strength of the pavement. The only remaining unknown than, is the thickness of the surface, which we derive from the curves.

All this is only an approximation, which has been improved by Nijboer[3] in two regards: First, by converting from the simplified single layer system to the more realistic multi-layer system and, secondly, in providing a conversion from static loading to dynamic loading.

As I say, I may oversimplify the situation, but I think that attack along these lines should prove to be very rewarding. Some of our own experiments indicate that Nijboer's curves and calculations provide a good approximation to actual measurements.

PROFESSOR HOUSEL: Does the panel have any comment?

DR. McLEOD: Everyone who has followed or reviewed the WASHO Road Test results is familiar with one of its most important findings, that the outer wheel path was weaker than the inner wheel path for the same flexible pavement thickness. At the 1954 A.A.P.T. meeting, Mr. W. N. Carey pointed out that the radical difference in performance of the two wheel paths could not be explained on the basis of moisture and density values for the underlying subgrade. Consequently, the outer wheel path of a flexible pavement with the usual gravel or earth shoulders appears to be inherently weaker than the inner wheel path.

It is a serious failing of the C.B.R., plate bearing, and similar empirical approaches to flexible pavement thickness design, that they indicate the outer wheel path to be equal in load supporting value to the inner wheel path. If the subgrade strength is the same for the outer and inner wheel paths, and if there is the same overlying thickness of base and surface, the outer and inner wheel paths must be of equal strength on the basis of C.B.R., plate bearing, and similar methods.

The same criticism applies to any of the elastic methods of flexible pavement design, Burmister's, Odemark's, etc. If the elastic properties

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[2] Van der Poël, C., Society of Plastic Engineers Journal, 11, 47 (Sept. 1955).

[3] Nijboer, L. W., De Ingenieur, Verkeerstechnick, 7 and 8, pp. 39-45 (1954).

of the subgrade and of the overlying layers of base and surface are identical for outer and inner wheel paths, these approaches to flexible pavement thickness design based upon elastic theory, must indicate exactly the same supporting value for the outer and inner wheel paths. The fact that the W.A.S.H.O. Road Test has so clearly demonstrated that for the same flexible pavement thickness, the outer wheel path is fundamentally weaker than the inner wheel path, provides the firmest evidence to date of the inability of elastic theory to provide an adequate basis for flexible pavement thickness design. Insofar as the dynamic testing method referred to by Mr. Heithaus is dependent upon elastic theory to explain the results of the test data it provides, the same criticism, and the same limitations in usefulness, applies to this dynamic test procedure also.

Assuming that the W.A.S.H.O. Road Test findings concerning the wide difference in strength between the outer and inner wheel paths are basically correct, we are compelled to look outside elastic theory, and beyond the C.B.R., plate bearing, and similar empirical approaches to flexible pavement design for an explanation of this observation. It seems to me that we must introduce considerations of the ultimate strength of flexible pavements, and of the plastic characteristics of each layer of the flexible pavement structure, to obtain a theoretical explanation for this very practical observation that the W.A.S.H.O. Road Test has pointed up so well.

Incidentally, on the basis of an ultimate strength approach to flexible pavement design described in a paper by myself at the A.A.P.T. meeting in 1954, a very simple explanation was offered for the observed difference in strength between the inner and outer wheel paths. However, there is not time to review it here.

PROFESSOR HOUSEL: Thank you, Dr. McLeod. You touched on a point I was going to ask, and I would like to emphasize. I assume that the relationships which you were talking about, Dr. Heithaus, were based upon the assumption of an elastic material. Is that correct?

DR. HEITHAUS: Yes.

PROFESSOR HOUSEL: Along that line I might point out that the assumptions of elasticity are four in number, that is, that you have first, continuity of stress, second, homogeneity, third, isotropy and, fourth proportionality between stress and strain, which is known as Hooke's Law. Of those four basic assumptions it is generally accepted among all the research workers in soil mechanics, and I don't know to what extent it may be among the asphalt paving technologists, that not one of these assumptions is accurately applied to the problem about which we are talking.

That bears very definitely on the point Dr. McLeod brought up.

Now we have come to a point in the meeting to cut off the general discussion to permit a summary of the symposium.

Mr. Chairman, I can turn the meeting back to you. If it is desirable, however, I can take a little time after you turn the meeting back to me to go over these other questions proposed by Mr. Vallerga.

CHAIRMAN NEVITT: We have fifteen minutes approximately. I want to stop right on time because of our schedule afterward. I would suggest we continue to get some discussion from the floor. I would like to suggest that we give the people who would like to talk about these items an opportunity, such as the effect of climate. We are testing the material not in some predetermined state but in the state that it will actually be when we suffer our greatest stress situation. That is just a suggestion, however.

PROFESSOR HOUSEL: As a matter of fact your suggestion fits in very well with the questions that Mr. Vallerga asked, which have not been discussed or have not been answered.

His question No. 5 is: What about fatigue properties of soil and surfacing materials?

I feel that has been covered in the discussion of elastic properties and by what Dr. Mack and some other discussers have said. Therefor we might pass that question and go to No. 6: How should climatic conditions be evaluated in a thickness design method?

I will call for volunteers from the panel on that. Dr. McLeod, I know you have something to say on that. Suppose you take about four minutes of well-chosen words on that subject.

DR. McLEOD: (Slide) This shows one of the slides you saw earlier, (Figure 48), indicating the influence of traffic volume on thickness requirements. For example, for only 100 coverages of the design wheel load or equivalent throughout the life of the pavement, the required thickness of flexible pavement is only 50 per cent of that needed for one million coverages of the design wheel load or equivalent in 25 years.

During the spring break-up period which lasts for about a month in northern climates, only about one-twelfth of the lifetime traffic is carried. One-twelfth of one million coverages is about 80,000 coverages, and the slide (Figure 48) shows that this number requires about 86 per cent of the thickness needed for one million coverages.

Could I have the next slide please? (Figure 53.) This slide presents results obtained by the Motl Committee of the Highway Research Board (from its study of the strength of flexible pavements throughout the year). During the spring break-up period, the bearing capacity drops to about 50 per cent of its fall value, and then gradually recovers during late spring, summer, and fall. This means that flexible pavement strength is not constant in northern climates, but is changing throughout the year. This variation seems to be caused by changes in subgrade strength due to the effect of frost action.

It is quite often recommended that flexible pavement thickness should be based upon the lowest subgrade strength, which would be the minimum point on this curve. However, it should be obvious that on this basis, the pavement would be overdesigned for every other period of the year. As a matter of fact, if designed on this basis, it would actually be overdesigned for even for the spring break-up period, as will be illustrated, because only about 80,000 coverages of the design wheel load are carried during the spring break-up periods in 25 years, instead of one million coverages.

The next slide please! (Figure 19.) The results reported by the Motl Committee have been checked by plate bearing tests on Canadian airports, and we have also found about 50 per cent loss in strength during spring break-up in the interior of Canada. For a wheel load of 12,000 pounds, if the subgrade strength in the late fall is 6,000 pounds on a 12-inch plate (0.2 inch deflection, 10 repetitions of load), the appropriate curve on this slide shows that about 10 inches of flexible pavement thickness is needed for capacity traffic. If the subgrade strength decreases to 50 per cent of its fall value during spring break-up, it becomes 3,000 pounds on a 12-inch plate (0.2 inch deflection, 10 repetitions of load) during this period. For this low subgrade strength, the slide shows that nearly 21 inches of flexible pavement thickness would be needed to support one million coverages of a design wheel load of 12,000 pounds or equivalent in 25 years. However, only about 80,000 coverages are carried during the spring break-up periods in 25 years, and the first slide (Fig. 48) showed that for this volume of traffic, only 86 per cent of the thickness needed for one million coverages was required. Consequently, the thickness requirement becomes 86 per cent of about 21 inches, or about 18 inches.

This illustrates our approach to the determination of the thickness of flexible pavement required to carry normal capacity traffic throughout the year including spring break-up periods. It is believed that the influence of any other climatic factors could be handled in a similar manner.

PROFESSOR HOUSEL: I think that contributes something to the last question.

Now I am going to try in a few minutes to present the closing summary that the chairman suggested.

We started out here with the suggestion that flexible pavement design could be subdivided into several phases, the first of which was an abstract problem of structural mechanics. In this would be considered simply the structural mechanics involved, including a specific load, a definite bearing capacity and a specified thickness.

There have been several discussers and several comments from the panel that may have given you some enlightenment on that subject.

As the second phase we discussed the properties of the materials and how they may be measured and how these properties may be incorporated in structural design. There have been a number of comments on that subject which I think may have been very helpful. These included discussions such as Dr. Mack's in which he pointed out the stress-strain characteristics of the different materials and similar comments and information from members of the panel and perhaps others.

Finally there is the third phase in which we try to bring into the picture the rest of the imponderable factors, the traffic capacity, wheel load and equivalent wheel loads and the effect of weather including some of the phenomena Dr. McLeod has just discussed. These are the more difficult things to evaluate in precise terms.

As a basis of correlating the several different phases, it is suggested that a design be set up in which there would be no failure or no component of the structure overstressed under any combination of environmental conditions or traffic load. This might be called a 100 per cent design. Such a design would simply be used as a reference design or standard. Then, as Dr. McLeod has just said, it is not necessary or practical to design for the weakest condition of the subgrade in all cases. That would cost too much, and is only a temporary condition lasting for several weeks so the accumulated deformation will not cause failure. Under such conditions it might be satisfactory to design for 50 per cent of that maximum standard while for a heavier load the design might be 75 per cent of that maximum. This would avoid a revision in the basic design every time it became necessary to meet increased traffic loads or more severe conditions of use. I believe that such a procedure would contribute a great deal to the development of a generally accepted method, applicable to a wider range of conditions and more acceptable to everybody concerned.

CHAIRMAN NEVITT: I trust you gentlemen have the same impression I have, that we have had a very interesting discussion. The panel has shown a grasp of the subject which has been illuminating to all of us. We haven't the answers to all the problems in the subject, but we have a rather systematic idea of what these problems are and the approach. In closing, I would just like to add an appeal to Professor Housel's concerning the point he made some time back, that various organizations must have a practical method of designing roads today, since they are building roads and can't wait until all these problems are settled. They have had to work out a method which expresses their best judgment and experience to date. They will continue to do that, but I hope they will add to the data, add to the impetus toward a rational design as near as we can get to that with our basic test methods today, so that as we design roads under present methods we nevertheless steadily progress towards better roads and cheaper roads, because this last is the most important point in this whole discussion. We must get the best results from our money for the benefit of the public as well as the benefit of asphalt roads.